**US Army Corps
of Engineers**
Waterways Experiment
Station

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Super-Heavy Aircraft Study

by *Walter R. Barker, Carlos R. Gonzalez*

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Prepared for U.S. Department of Transportation

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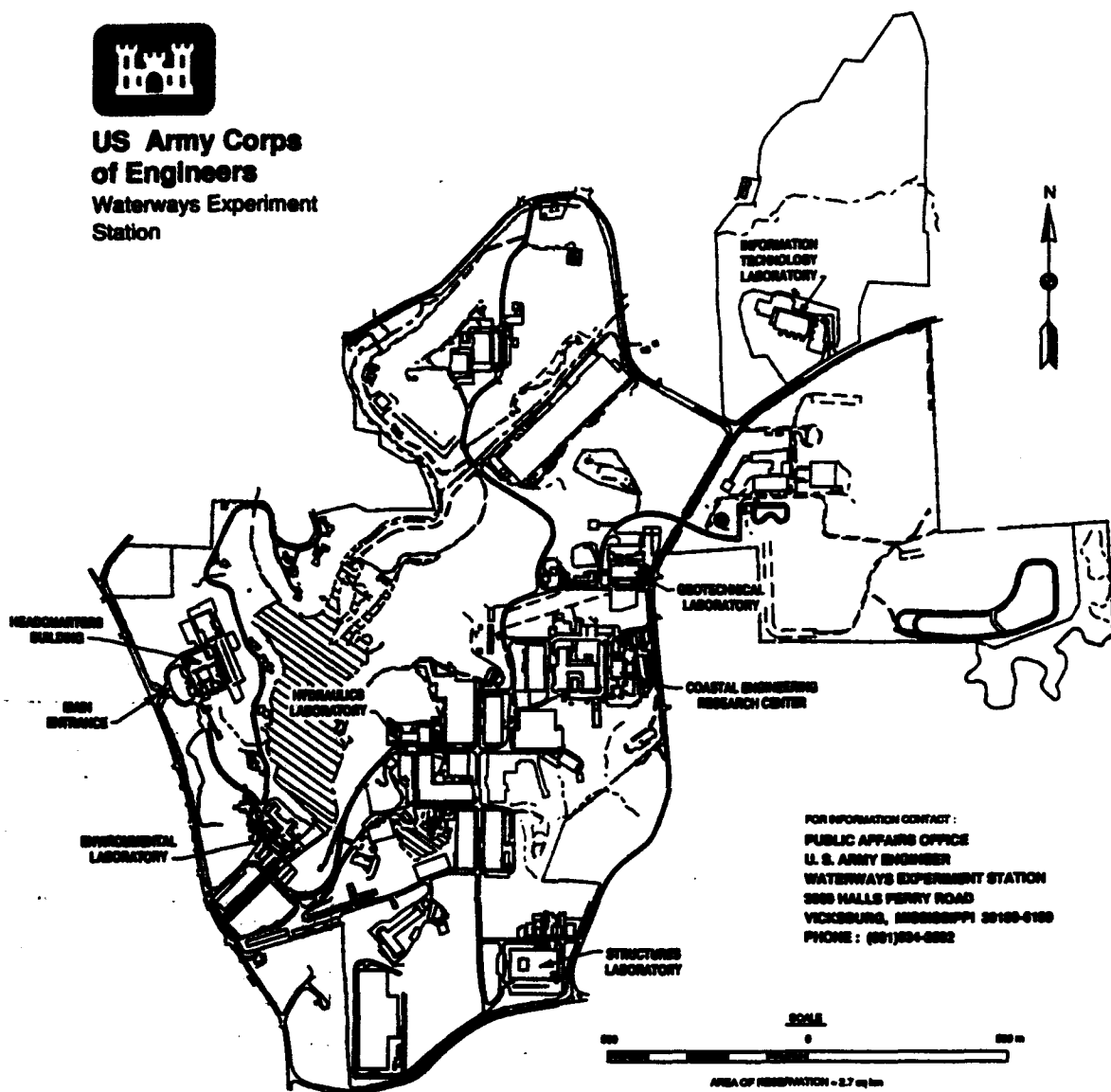| Accesion For	
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US Army Corps
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Waterways Experiment
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PREFACE

The study reported herein was sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), U.S. Air Force, U.S. Army, and the Federal Aviation Administration (FAA) under the effort "Design for Heavy-Weight Aircraft." The Technical Monitors were Mr. Paige Johnson, HQUSACE, Mr. John Rice, FAA, and Mr. Jim Greene, U.S. Air Force.

The study was conducted at the U.S. Army Engineer Waterways Experiment Station (WES) from May 1991 through March 1992 by the Pavement System Division (PSD) of the Geotechnical Laboratory (GL). This report was written by Dr. Walter R. Barker and Mr. Carlos R. Gonzales, PSD, under the supervision of Dr. G. M. Hammitt II, Chief, PSD; and Mr. Jim Hall, Chief, System Analysis Branch. Mr. Richard Ahlvin, a WES consultant, assisted in the collection and analysis of data. The work was performed under the general supervision of Dr. William F. Marcuson III, Director, GL.

Dr. Robert W. Whalin was the Director of WES. COL Bruce K. Howard, EN, was the Commander during the preparation of this report.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
	inches	*2.5	centimeters	cm
	feet	30	centimeters	cm
	yards	0.9	meters	m
	miles	1.6	kilometers	km
	AREA			
	square inches	6.5	square centimeters	cm²
	square feet	0.09	square meters	m²
	square yards	0.8	square meters	m²
	square miles	2.6	square kilometers	km²
	acres	0.4	hectares	ha
	MASS (weight)			
	ounces	28	grams	g
	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
	teaspoons	5	milliliters	ml
	tablespoons	15	milliliters	ml
	fluid ounces	30	milliliters	ml
	cups	0.24	liters	l
	pints	0.47	liters	l
	quarts	0.95	liters	l
	gallons	3.8	liters	l
	cubic feet	0.03	cubic meters	m³
	cubic yards	0.76	cubic meters	m³
	TEMPERATURE (exact)			
	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm²	square centimeters	0.16	square inches	in²
m²	square meters	1.2	square yards	yd²
km²	square kilometers	0.4	square miles	mi²
ha	hectares (10,000 m²)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m³	cubic meters	35	cubic feet	ft³
m³	cubic meters	1.3	cubic yards	yd³
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

* 1 in. = 2.54 (exactly). For other exact conversions and more detailed tables, see NBC Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.
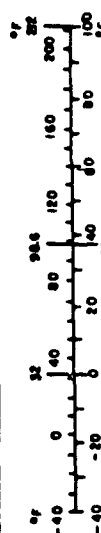
INTRODUCTION

GENERAL

Airport congestion at major hub airports is dictating a need for larger and heavier aircraft to carry more passengers such that the demand for air travel can be met without an increase in aircraft movements. Already under development are commercial aircraft having gross weights in excess of one million pounds. For such an aircraft to be a commercially viable option, the aircraft must be suitable to operate from most of the major civil airports. There would also be considerable impact on military airfields in that many military operations require the use of civil aircraft. In the design of the landing gear for the new aircraft, it has become apparent that by the current flexible pavement procedure for computing the effect of aircraft on pavement performance, the new heavy aircraft will be more damaging than is permitted by the Federal Aviation Administration (FAA) guidelines. The aircraft designers suspect the method for computing the equivalent single-wheel load (ESWL) is flawed when it is applied to the new type of aircraft gear.

BACKGROUND

The flexible pavement design procedure used by the FAA, the Army Corps of Engineers, and the Air Force employs the California Bearing Ratio (CBR), aircraft loading, tire contact area, and traffic volume as design parameters. The development of the classic CBR equation is presented by Turnbull and Ahlvin[1], Ahlvin[2], and Ahlvin[3]. The CBR equation was originally developed for single-wheel gears and for a traffic level of 5,000 coverages.

To accommodate multiwheel aircraft in the design of flexible pavements, a methodology for computing an ESWL was introduced into the CBR equation.[2] Ideally, the ESWL should be the loading on a single-wheel load which will be equivalent in performance (i.e., passes to failure) to the multiwheel gear. In practice, the ESWL is defined as a load on a single tire having the same contact area as a tire in the multiwheel gear, which will provide the same deflection at a specified point in the pavement system as the multiwheel load. The deflection on which the ESWL is based is the maximum deflection as computed by the Boussinessq single-layer half-space theory at a specified depth under the multiwheel gear. This results in the ESWL for a given aircraft being a function of the depth for which the ESWL is to be computed.

In the early studies, several parameters were considered for determining the ESWL. The principal two were the shear stress and vertical deflection. From the data available at the time, the deflection-based ESWL appeared to provide the best design parameter for use in the CBR equation. It was realized during the development of the deflection-based ESWL that if aircraft were developed having widely spaced multiwheel gears, the deflection-based ESWL for that gear would probably under predict passes to failure (personal communication with Mr. R. G. Ahlvin). In the 1960's and 1970's, prototype testing of multiwheel gear verified that the ESWL based on deflection under predicted the number of passes to failure. To compensate for the over prediction of the ESWL, a thickness adjustment factor for multiwheel aircraft and traffic volume

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was introduced[4,5]. The thickness adjustment factors (α-factors) were a function of number of tires and level of traffic in terms of coverages.

In 1990, Mr. O. W. Preston from McDonnell-Douglas Aircraft Corporation, motivated by a long-held suspicion that the deflection is a poor parameter for the prediction of pavement performance, undertook a study to evaluate the test data from the multiwheel load tests conducted at the U.S. Army Engineer Waterways Experiment Station (WES). As a result of the study, Mr. Preston developed a design procedure based on the horizontal shear strain[6]. In this procedure, referred to in this report as the Preston's slope method, the horizontal shear strain is computed from the slope of the vertical deflection basin for a plane at the top of the subgrade using the Boussinessq deflection factors. The thickness of pavement above this "plane" is determined from criteria developed from the test section data. Mr. Preston found that the use of this methodology for pavement design eliminated the requirement for thickness reduction factors and resulted in reduced design thicknesses for multiwheel aircraft.

As a direct result of Mr. Preston's study and in anticipation of the operation of new heavy multiwheel aircraft, the U.S. Air Force, the FAA, and the U.S. Army Corps of Engineers engaged the WES to undertake a study to evaluate the available test data in light of Mr. Preston's study and newer analytical methods for computing pavement response parameters.

PAVEMENT PERFORMANCE DATA

GENERAL

To investigate the correlation between the proposed design parameters and pavement performance, available test section data were revisited and reanalyzed using a layered elastic methodology. Most data were obtained from accelerated traffic test sections and consisted of pavement thicknesses, subgrade strengths, gear configurations, gear loads, and coverages to failure.

AVAILABLE TEST SECTION DATA

The data gathered for this investigation are summarized in Table 1. The data in this table present the readily available performance data for flexible airfield pavements. These data have been generated by the U.S. Army Corps of Engineers over the past 50 years in work that has been sponsored by the Army, Air Force, and FAA. This table presents the 37 test points considered for analysis along with their respective references from which they were obtained. Of these data, one test was a nonfailure, and four tests were borderline failures. In the table, traffic is described by the gear type, tire spacing, gear load, tire contact area, and coverages to failure. The total pavement thickness above the subgrade, subgrade CBR, and failure condition describe the pavement structure.

In compiling the data, Corps of Engineers' reports were searched for test data and all data found was screened for inclusion in the data base. The screening was based on adequacy of structure data and description of pavement performance. For the most part, nonfailures were not included in the data. Data point number 36 in Table 1 was an exception because this data point was from the test section for development of criteria for the C-5 aircraft and was particularly applicable to this study. After screening, the remaining data consisted of a variety of pavements with a range of traffic levels to failure, aircraft loading, subgrade strengths, and thicknesses. Figures 1, 2, and 3 give the cumulative distribution of the test section data for coverages to failure, subgrade CBR values, and total pavement thicknesses, respectively. Figure 1 shows that the maximum traffic to failure was approximately 7,000 coverages and the minimum traffic to failure was 6 coverages. The median level of traffic to failure was approximately 300 coverages. Subgrade CBR values range from as low as 3.7 to as high as 35, with a median CBR value of 7. Total pavement thicknesses range from 5 to 49 inches, with a median thickness of 16 inches. The applied loading to these pavements also consisted of a range of load magnitudes and number of tires per gear which were representative of contemporary aircraft. Single-wheel gears, twin gears, twin-tandem gears, and delta-twin-tandem gears varying from 15 kips to 360 kips per gear were available.

The range of the test data is important when considering the extent to which the data are extrapolated. For example, in computing the aircraft classification numbers (ACN) for ultralow subgrade strengths, 10,000 coverages and a 3 CBR are used for computing the ACN. The ACN for this ultralow strength subgrade for some aircraft already in existence is in excess of 100,

Table 1

Available Test Section Data Used

Reference No.[1]	Test Point	Gear Type	Tire Spacing (in)	Gear Load (kips)	Tire Contact Area (sq in)	Pavement Thickness above Subgrade (in)	Asphalt Thickness (in)	Base Thickness (in)	Subbase Thickness (in)	Subgrade CBR	Coverage to Failure	Failure	Borderline	Non-Failure
3	1	Single Wheel	N/A	200	1,501	38.0	7.0	13.0	18.0	8.0	150	.		
3	2	Single Wheel	N/A	200	1,501	44.0	7.0	15.0	22.0	8.0	1,700	.		
3	3	Single Wheel	N/A	200	1,501	18.0	8.0	6.0	0.0	18.0	10	.		
3	4	Single Wheel	N/A	200	1,501	20.5	6.5	14.0	0.0	18.0	60	.		
3	5	Single Wheel	N/A	200	1,501	23.5	6.5	14.5	2.5	15.5	360	.		
3	6	Single Wheel	N/A	200	1,501	20.0	7.0	14.0	9.0	17.5	1,500	.		
3	7	Single Wheel	N/A	200	1,501	48.0	6.0	14.0	28.0	8.0	1,300	.		
4	8	Single Wheel	N/A	15	250	10.0	1.0	4.0	5.0	8.0	3,780	.		
4	9	Single Wheel	N/A	15	250	10.0	1.0	4.0	5.0	9.9	3,780	.		
6	10	Single Wheel	N/A	60	350	15.0	3.0	4.0	8.0	3.7	6	.		
6	11	Single Wheel	N/A	60	285	24.0	3.0	6.0	15.0	4.4	200	.		
7	12	Single Wheel	N/A	30	285	12.0	1.5	5.5	5.0	3.7	120	.		
7	13	Single Wheel	N/A	30	150	12.0	1.5	5.5	5.0	14.0	218	.		
8	14	Single Wheel	N/A	30	150	12.0	1.5	5.5	5.0	7.0	178	.		
8	15	Single Wheel	N/A	30	150	5.0	5.0	0.0	0.0	8.0	203	.		
10	16	Single Wheel	N/A	10	91	10.0	3.0	7.0	0.0	6.0	40	.		
6	17	Twin	37	70	320	10.0	3.0	7.0	0.0	27.0	1,500		.	
6	18	Twin	37	70	320	10.0	3.0	7.0	0.0	35.0	2,000		.	
8	19	Twin	37.5	100	288	18.0	3.0	5.5	6.0	35.0	328			
6	20	Twin	37.5	105	350	25.0	1.0	12.0	12.0	24.0	2,000		.	
6	21	Twin Tandem	36	160	290	33.0	3.0	6.0	24.0	14.0	7,189			
9	22	Twin Tandem	44 x 58	240	290	41.0	3.0	6.0	32.0	4.0	40	.		
7	23	Twin Tandem	44 x 58	240	380	14.0	3.0	5.5	0.0	4.0	2,000			
7	24	Twin Tandem	31.5 x 60	160	273	14.0	3.0	5.5	0.0	20.0	2.0	.		
7	25	Twin Tandem	31.5 x 60	200	273	20.0	3.0	17.0	0.0	18.0	610			
8	26	Twin Tandem	31.5 x 60	390	180	19.0	1.5	14.5	0.0	27.0	2,000			
6	27	Twin Tandem	31.5 x 58	120	180	16.0	1.5	14.5	0.0	15.0	1,500		.	
6	28	Twin Tandem	31.5 x 58	120	190	16.0	1.5	14.5	0.0	6.0	90	.		
8	29	Twin Tandem	44 x 58	160	290	24.0	3.0	6.0	15.0	12.0	310	.		
6	30	Twin Tandem	44 x 58	200	287	33.0	3.0	6.0	24.0	5.8	140	.		
6	31	Twin Tandem	44 x 58	240	287	33.0	3.0	6.0	24.0	5.8	3,860		.	
6	32	Twin Tandem	44 x 58	380	285	15.0	3.0	6.0	6.0	4.4	600	.		
6	33	C-5A 12 Tires	(34-53-34)-40x95x230	380	285	24.0	3.0	6.0	15.0	3.7	6	.		
6	34	C-5A 12 Tires	(34-53-34)-40x95x230	380	285	33.0	3.0	6.0	24.0	4.4	104	.		
6	35	C-5A 12 Tires	(34-53-34)-40x95x230	380	285	41.0	3.0	6.0	32.0	3.9	1,500			
6	36	C-5A 12 Tires	(34-53-34)-40x95x230	380	285	24.0	3.0	6.0	15.0	5.0	3,850			
6	37	C-5A 12 Tires	(34-53-34)-40x95x230	380								198	.		

[1] Reference numbers refer to numbers listed in the Reference Section.

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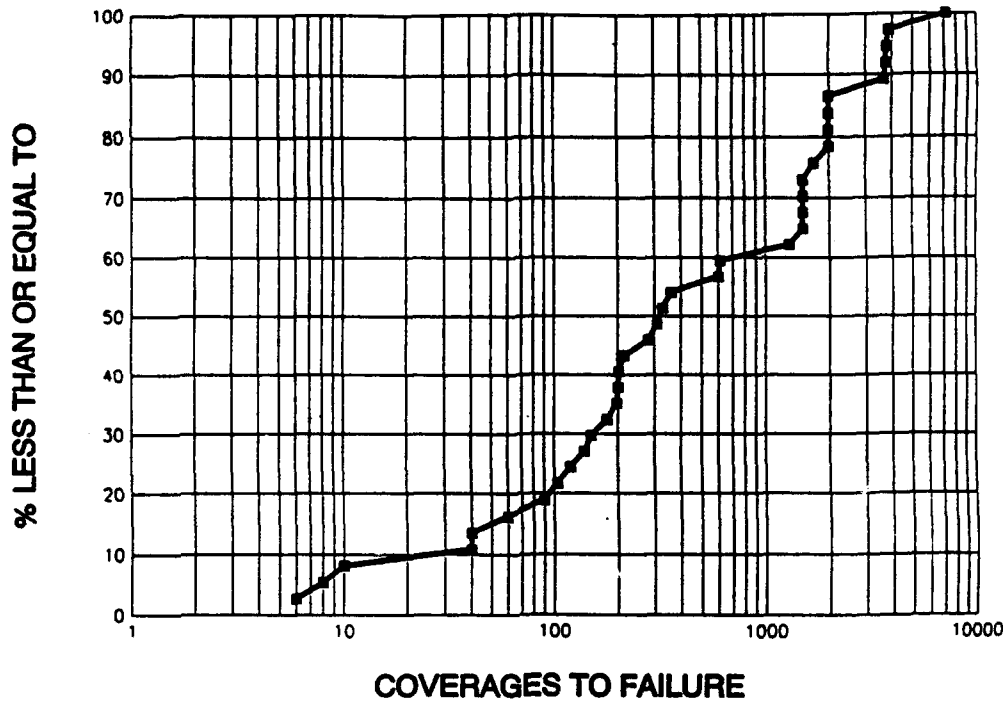
Figure 1. Cumulative distribution of coverages to failure in the test data base
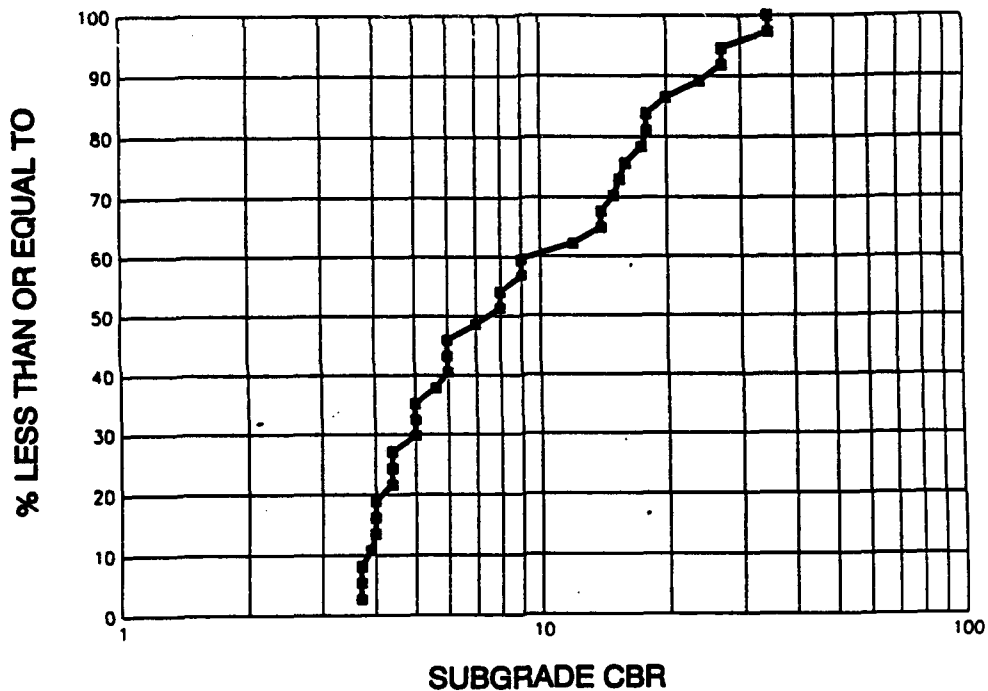
Figure 2. Cumulative distribution of subgrade CBR values in the test data base

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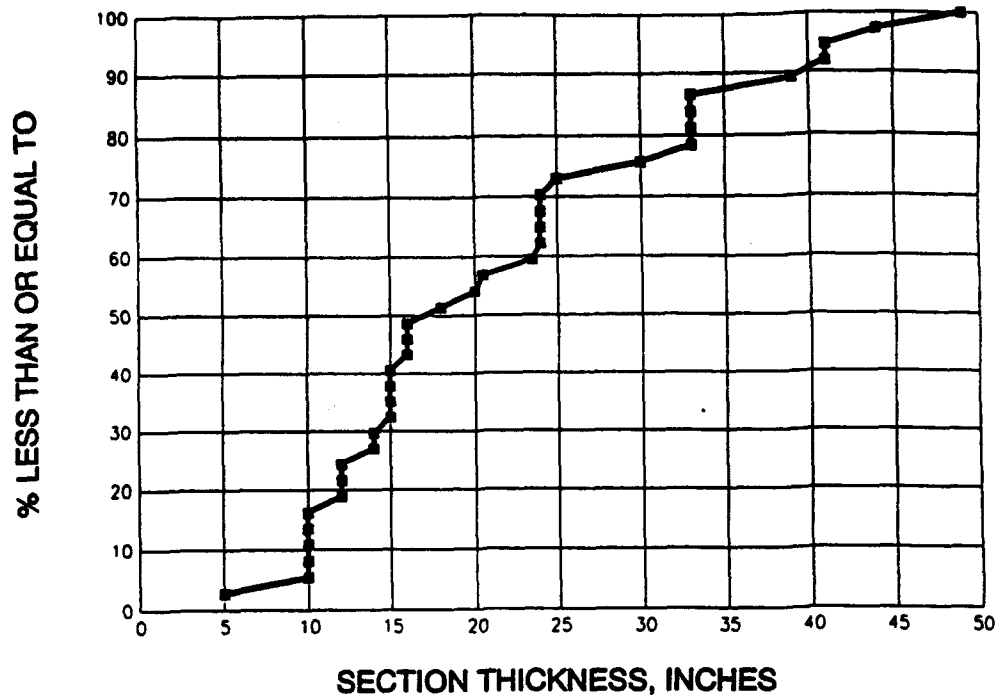
Figure 3. Cumulative distribution of total pavement thicknesses in the test data base

indicating the thicknesses required would be in excess of 65 inches. This indicates that even in computing ACN, the data are being extrapolated far beyond the bounds of the available data. In actual pavement design, the data are being extrapolated to an even greater extent. For instance, considering that the FAA design procedure provides for 25,000 annual departures, and that some major airports are considering designs for a 40-year pavement life, a design traffic in the order of 1,000,000 total departures would have to be expected. It is essential that the methodology used to extrapolate the data has a sound theoretical basis and that the data are used as a means of verification of the methodology.

DATA ANALYSIS

GENERAL

The initial attempt at the reanalysis of the test data was to modify the current methodology to reduce the effect on the computed ESWL of widely spaced tires of an aircraft gear. This approach assumed that the Boussinessq theory would compute more deflection at greater distances from the tire than would exist in an actual pavement. This has in fact been long recognized and different correction procedures have been implemented. In the earlier studies at WES, a 20-radii cutoff procedure had been applied. In his analysis, Mr. Preston[6] uniquely applied a 25-radii cutoff. The current computer program used for computing the ESWL factor does not apply any cutoff distance for the computing deflection. The result is that all tires regardless of spacing will have a contribution to the ESWL factor. It was also extremely desirable to maintain the ESWL concept and retain the basic ESWL/thickness/CBR relationship of the current design procedure in the analysis methodology. The modification should involve only the method in which the ESWL is determined. An obvious modification would be to use different radii cutoff for computing a deflection-based ESWL. The other obvious choice would be to use a different response parameter as the basis for the ESWL. In computing the response parameters, a Boussinessq model or an elastic multilayered model could have been chosen.

After conducting the study for the initial approach, the benefit of maintaining the basic ESWL/thickness/CBR relationship was questioned. A second approach was developed in which the response parameters of the test sections were related directly with the performance of the test sections. To compute the response parameters, both the Boussinessq model and the elastic layered model were available. The response parameters were determined at the top of the subgrade. In addition to deflection the response parameters considered were the vertical strain, horizontal shear strain, maximum shear strain, and the octahedral shear strain. The irony of using shear strain as a pavement response parameter is that this was one of the parameters originally suggested for computing the ESWL. At that time it was felt that ESWL's based on shear strain would not be conservative. Another factor that may have been a consideration in selecting the deflection over shear strain was that the deflections due to multiwheel loading could be determined more readily by means of tables and charts.

COMPUTER PROGRAMS

WESWL Program

For years WES has been utilizing a computer program developed by General Dynamics Corporation for computing the ESWL curves for aircraft. The computer program uses the Boussinessq model for an elastic half-space for computing deflection factors at the top of the subgrade from which the ESWL is computed. In 1991, WES developed a new ESWL program specifically for the microcomputer. This program, WESWL[7], is similar to the earlier program but utilizes different integration and search routines. For this study, the WESWL program was modified such that different radii cutoff for computing the deflection could

be considered. In the use of a radii cutoff, the deflection at the designated
cutoff distance (from the center of the load) is computed. All deflections
computed for distances less than the designated cutoff distance are adjusted
by the equation:

$$D = d - (x_1/x_c)d_c$$

where

> D — the adjusted deflection at distance x1 used to compute the to[...]
> deflection for a multiwheel gear
>
> d — the deflection computed by Boussinessq theory at a distance x1
> from the center of the loaded area
>
> x_1 — the distance for the search point to the center of the loaded area
>
> x_c — the cut off distance which is equal the radius of the tire times
> the cutoff radii
>
> d_c — the deflection computed by Boussinessq theory at the cutoff
> distance from the center of the loaded area

If the distance from the search point to the center of the tire is
greater than the cutoff distance, the deflection was assumed to be zero.
Thus, a tire at a distance greater than the cutoff distance would not have any
contribution to the ESWL.

Figure 4 provides a comparison of data obtained by running the WESWL
program for different radii cutoff distances. Figure 4 also shows data
obtained from Preston's analysis in which the ESWL was determined using the
slope method. The data clearly show that for cutoff distances less than
20 radii, the ratio of the ESWL at a given depth to the single-wheel load is
very sensitive to the cutoff distances. For distances greater than 20 radii,
there are little differences in the ESWL ratio.

ACNLEA Program

In the course of the project, the computer program "ACNLEA" was devel-
oped. This code uses a layered elastic model for computing the pavement
response to load. The layered elastic analytical model chosen to be incorpo-
rated into the ACNLEA computer program was the JULEA computer code. The JULEA
code was written for a single-load analysis by Dr. Jacob Uzan (personal corre-
spondence) and was modified at WES for multiload analysis. The JULEA code has
been used in the development of the elastic layered design procedures and in
the evaluation of pavements using elastic layered theory. The JULEA computer
program allows the calculation of the design parameters in a system of elastic
layers at any depth and at any point on a horizontal plane. A search grid was
added to the ACNLEA basic computer code to calculate values of the selected
parameters at locations defined by a grid and to sort the data to obtain the
maximum values. By the use of superposition, the computer program permits the
modeling of any gear configuration. The ACNLEA program has the capability of

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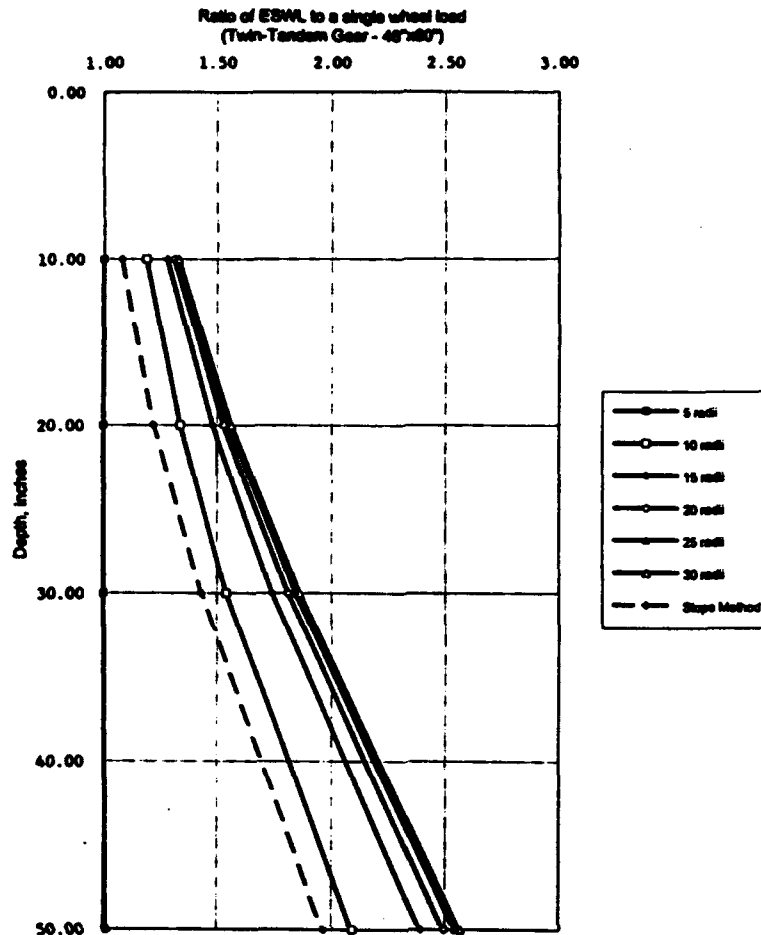
Figure 4. Comparison of data from the WESWL computer program

analyzing both single-layer and multilayer systems. The single-layer and multilayer capabilities allowed the analysis of the test sections both as a single-layered system and as a multilayered system. The program automatically assigns material properties depending on which system is chosen to represent the pavement structure.

In addition to the analysis of the test section data, the program has the capabilities of analysis of pavements considering different performance criteria, analysis of equivalent single-wheel loads for different aircraft, and the computation of strain-based ACN values for an aircraft. A description and a user guide for ACNLEA is provided in Appendix A. The computer program and pavement performance criteria built into it have not been approved for use.

LAYERED ELASTIC AIRCRAFT CLASSIFICATION NUMBER

The ACNLEA computer program contains performance criteria for pavement design based on subgrade strain. The criteria imply that all loads producing the same subgrade strain magnitude will be equivalent in terms of pavement performance. If this is true, then aircraft can be rated on the basis of a

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standard wheel that will produce the same subgrade strain magnitude (i.e., an equivalent standard wheel in terms of performance). In the ACNLEA computer program the loading of a standard wheel is computed which will produce the same strain as the strain produced by the aircraft loading. This standard wheel load represents the equivalent standard wheel load for that aircraft. For a given aircraft, the equivalent standard wheel load will be a function of the pavement thickness, the layer properties (modulus of elasticity and Poisson's ratio), and the aircraft loading. The computer program generates standard pavement sections which would eliminate the layer properties from the list of independent parameters. With the standard sections the difference caused by different subgrade strengths would be minor and most likely could be disregarded. The ACN value of an aircraft could then be presented as a function of aircraft loading and thickness of the standard pavement. For computation of the pavement classification number (PCN) for an existing pavement, a method would have to be developed for converting actual pavement sections to the standard pavement sections. This could be accomplished by using a design procedure similar to the present method for determining the PCN.

MATERIAL CHARACTERIZATION

The layered elastic analysis requires the characterization of pavement structures by two elastic constants: modulus of elasticity and Poisson's ratio. The basic assumptions when using the elastic model are that (1) the pavement system is a layered continuum, (2) the layers are homogeneous and isotropic, (3) the bottom layer extends to infinity, (4) the interface between layers is either bonded, frictionless, or partially bonded, and (5) the loads are applied as circular areas of pressure.

For the multilayer analysis, the actual thicknesses of the test sections were used to define the layers composing their pavement structure. The modulus of elasticity for the subgrade materials was estimated by the empirical relationship $E_{subgrade}$ (psi) = 1,500*CBR. The Poisson's ratio for the subgrade materials was assumed to be 0.4. Modulus values for the granular layers were empirically assigned as described by Barker and Brabston.[8] The procedure is based on relationships developed for resilient modules of unbound granular layers as a function of the layer thickness and type of material. Asphalt surface layers were assumed to have a modulus of elasticity of 250,000 psi and a Poisson's ratio of 0.5. The interface condition between all layers was considered to be fully bonded. Figure 5 illustrates a multilayer system used in the analysis.

For the single-layer analysis, the sum of the test section thicknesses above the subgrade were used as the depth at which the pavement response parameters were computed. The single-layer above the subgrade was assumed to have the same elastic constants as the subgrade material. Subgrade materials with CBR values greater than 20 were considered to have a maximum modulus value of 30,000 psi.

An elastic-layered structure was set up for each test section point and analyzed with the ACNLEA computer program for the applied loading on each test section. The maximum response parameters were then determined for each test section to develop the performance criteria. Single-layer analyses were

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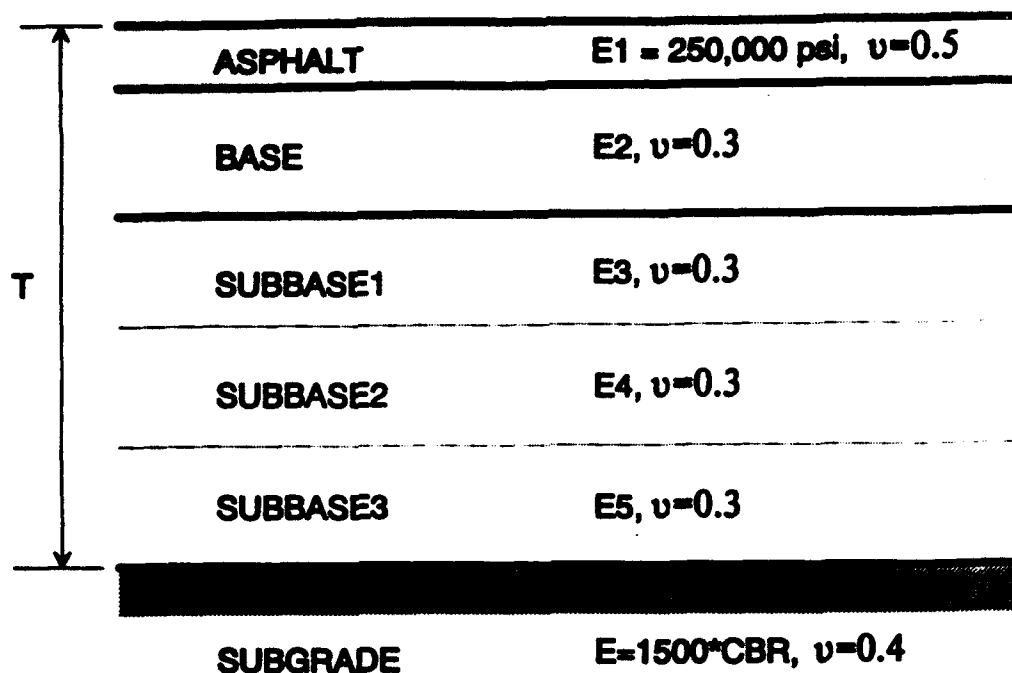
Figure 5. Test section parameters for a multilayer system

performed to compare results with the Corps of Engineers procedure and Preston's slope method[6] which is based on a single-layer system.

RESPONSE PARAMETERS

Earlier in this report it was stated that because of the limited ranges of the test data with respect to subgrade strengths, gear loading, and traffic level, extrapolation is required beyond the ranges of the test data and that selection of the parameter(s) for extrapolation must be soundly based. It has been recognized that the primary cause of pavement rutting has been shear deformations. The current CBR design procedure was developed to basically prevent such shear deformations. The logical parameters for consideration are deflection, maximum shear strain, vertical strain, horizontal shear strain, or octahedral shear strain. The deflection is the parameter currently used for computation of the ESWL. Strain parameters are considered in lieu of stress because past analyses indicate that the use of the strain provides a means of indirectly considering subgrade strength. The fact that in these analyses the modulus of elasticity of the subgrade was obtained from the CBR directly connects the strain relationships to the CBR. In considering the problem of multiwheel gear the attenuation of the response parameters with distance must be a consideration. To illustrate this, Figure 6 shows how different response parameters attenuate for a single-wheel loading. The response for multiwheel aircraft is computed by superimposing the response from the individual wheels. The vertical deflection and vertical strain can be superimposed directly, but the other parameters must be obtained by superposition of the strain tensors. The maximum shear strain, the octahedral strain, and the maximum horizontal shear strain are computed maximum strain tensors. The data in Figure 6

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SINGLE WHEEL, 50 KIPS, CBR=10, 40 INCHES DEEP
MULTI-LAYER SYSTEM
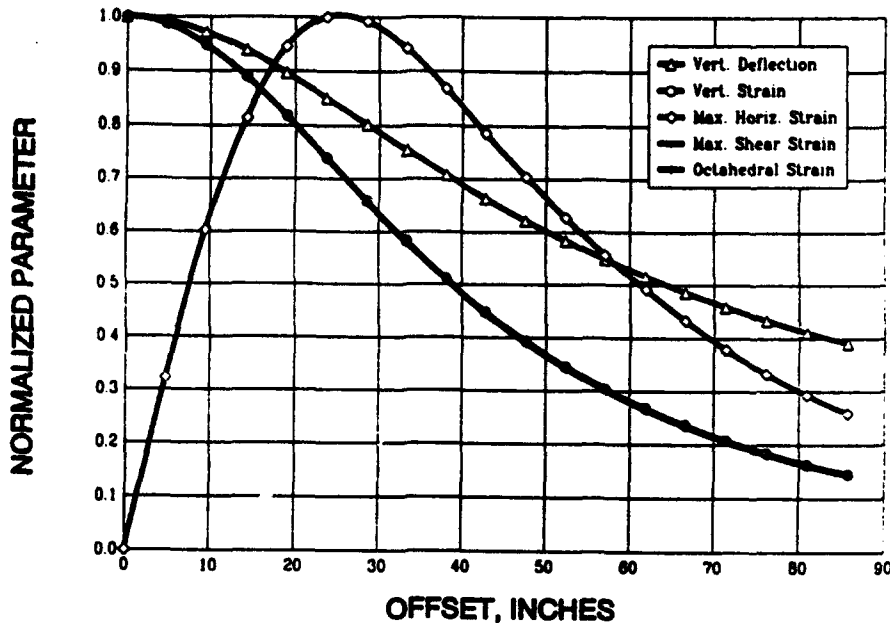
Figure 6. Attenuation of pavement response parameters with distance from point of loading

indicates that the vertical strain, maximum shear strain, and octahedral strain, attenuate essentially at the same rate and at a higher rate than the horizontal shear strain and the deflection.

BOUSSINESSQ ANALYSIS

The first approach of this study was to develop a performance criteria based on the ESWL and using deflection computed at the top of the subgrade for determining the ESWL and the classical CBR equation for the relationship between ESWL, subgrade strength, and thickness. This approach is the same as the current design procedure except that different cutoff distances were used to compute the ESWL. The development of the WESWL computer program permitted the calculation of the ESWL for selected cutoff distances. For each data point a thickness reduction factor (α-factor) was calculated based on the ESWL values from the different cutoff distances and the CBR equation. The α-factor is computed for each test section by first computing the ESWL using the program WESWL. From the ESWL and the tire contact area, the ESWL contact pressure (p) is determined. Finally, the Corps of Engineers CBR equation is solved for the α-factor as shown.

$$\alpha = T \ / \ [\sqrt{A} \cdot f(CBR/p)]$$

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where

  a = thickness reduction factor (α-factor)
  T = total pavement thickness, inches
  A = loaded contact area, square inches
  CBR = subgrade CBR
  p = contact pressure for the equivalent single wheel, psi

$$f(CBR/p) = -0.0481 - 1.1562 \left[\log \frac{CBR}{p} \right] - 0.6414 \left[\log \frac{CBR}{p} \right]^2 - 0.4730 \left[\log \frac{CBR}{p} \right]^3$$

Figures 7 and 8 present the data for the α-factor analysis with cutoff distances of 8 and 12 radii, respectively. In the figures the α-factor is presented as a percent of design thickness. Also presented in Figures 7 and 8 are the regression curves for both multiwheel and single-wheel data. It should be noted that for single loading the cutoff distance does not apply since the ESWL is always equal to the single-wheel load. The regression curve for the single-wheel data should agree with the load repetition factors currently being used for single-wheel loading. As can be seen in Figures 7 and 8, the published α-curve of a single wheel falls directly on top of the single wheel regression line obtained from the analysis. In comparing the regression curves for multiwheel data with the regression curve for the single wheel data, it is seen that by the proper selection of a cutoff distance, a curve can be determined which would be common to both multiwheel and single-wheel gear.

MULTILAYER ANALYSIS

Equivalent Single-Wheel Load Criteria

As in the Boussinessq analysis, there was a strong desire to develop performance criteria based on the ESWL concept using the classical CBR equation for the relationship between ESWL, subgrade strength, and thickness. Because of the long term use of the CBR equation in airport pavement design, there still existed a sense of loyalty to the relationship between CBR, load, and thickness. The approach for multilayered analysis was the same as was used for Boussinessq analysis except that in addition to deflection, strain parameters are used to compute the ESWL. The availability of the ACNLEA computer program permitted the calculation of the ESWL for multilayer pavement systems. For each data point, an α factor was calculated based on the ESWL values from the different strain values computed at the top of the subgrade and the CBR equation. The steps required to calculate the α-factors are

(1) For each test point the pavement structure is established by modeling each layer with the elastic layer constants (modulus of elasticity and Poisson's ratio).

(2) Using the elastic layer computer program, the response of a single-wheel from the gear is computed and expressed in terms of the selected response parameter, $SW_{response}$.
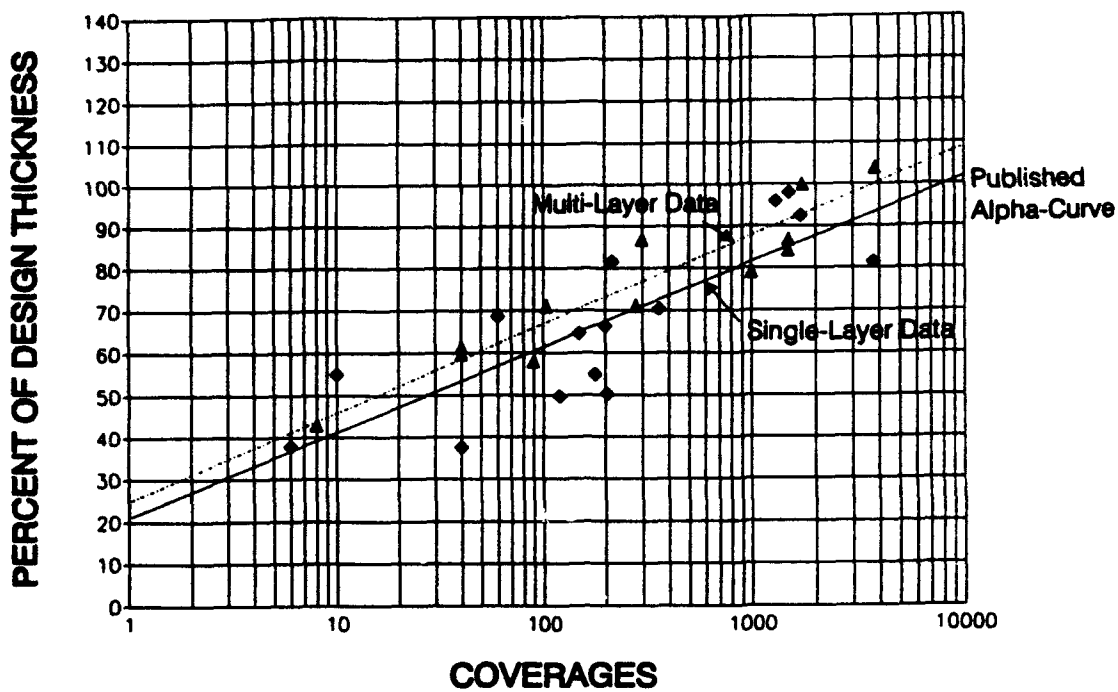
13

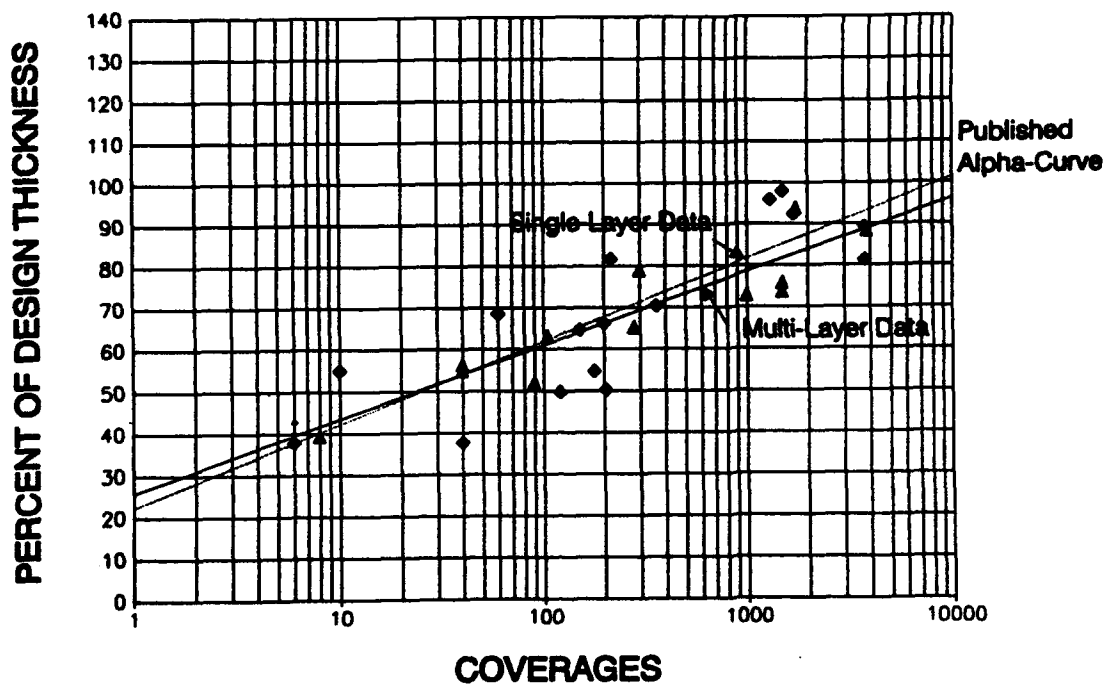**Figure 7.** Plot for the α-factor analysis for an 8-radii cutoff distance

Figure 8. Plot for the α-factor analysis for a 12 radii cutoff distance

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(3) The response of the gear (multiwheel) is calculated and expressed in terms of the selected response parameter, $MW_{response}$.

(4) The equivalent single-wheel load is calculated with the equation

$$ESWL = Single\text{-}wheel\ Load * \left(MW_{response}/SW_{response}\right)$$

(5) The Corps of Engineers CBR equation is solved for the α factor the same way as is done for the Boussinessq analysis.

Figures 9, 10, 11, 12, and 13 present α-plots based on ESWL values obtained from the maximum vertical deflection, maximum vertical strain, maximum horizontal shear strain, maximum shear strain, and maximum octahedral strain parameters calculated on top of the subgrade, respectively. In Figure 9 it can be seen that the data of multiwheel gears is well below the data for single-wheel gears. A comparison of the α-plots based on the strain parameters (Figures 10, 11, 12, and 13) revealed that the multiwheel data falls with the single-wheel data and that the data can be fit with one regression curve. This implies that using strain parameters as the basis for the calculations yields criteria which can be independent of gear type.

In comparing the data for the different criteria (Figures 10 through 13), it is not apparent that a single criteria provides a superior relationship over any other criteria. The data for all the criteria contain considerable scatter which could not be attributed to other parameters such as gear type, subgrade strength, or pavement thickness.

Strain Criteria

Another analytical approach was to correlate directly the computed strain values at the top of the subgrade with the performance (in terms of coverages to failure) of the test sections. This analytical approach would not utilize the CBR equation in the development of the criteria nor in the prediction of pavement performance in pavement design. Instead of plotting α-curves and using the CBR equation as the performance criteria, new criteria were developed for each strain parameter considered. In the development of the criteria, each of the test sections were analyzed using the ACNLEA computer program. The test sections were modeled as layered elastic systems with the layer properties determined as previously described. The loads applied to the test sections were modeled as circular areas of uniform pressure. Table 2 contains the values of both deflections and strains computed in the analysis of the test data. Figures 14 through 18 show the plots and regression fits of the data. The data for the deflection parameter (Figure 14) contains scatter that can clearly be attributed to gear type, indicating that a single criteria curve based on deflection would not be appropriate. The plots for the strain data produced regression curves very similar with no obvious superior relationship. None of the strain plots showed a significant difference between multiwheel and single-wheel data. This is illustrated in Figure 19 where the data for the maximum shear strain for the multiwheel and the single-wheel

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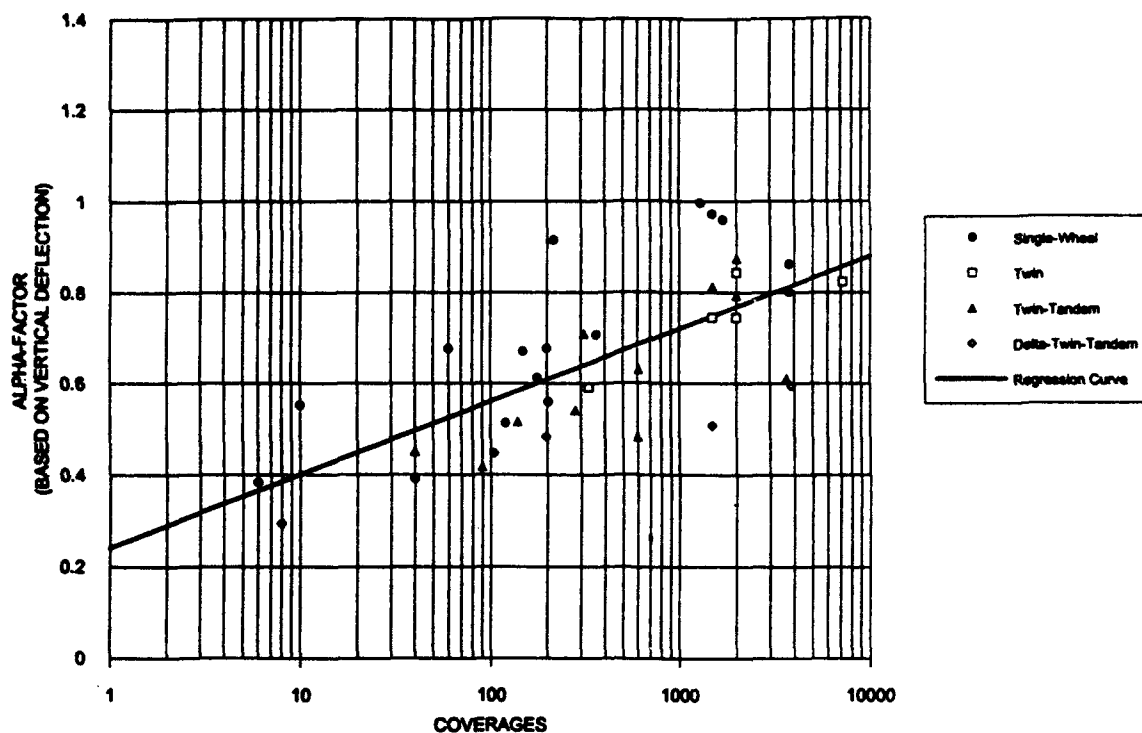
Figure 9. Plot for the α-curve criteria based on vertical deflection

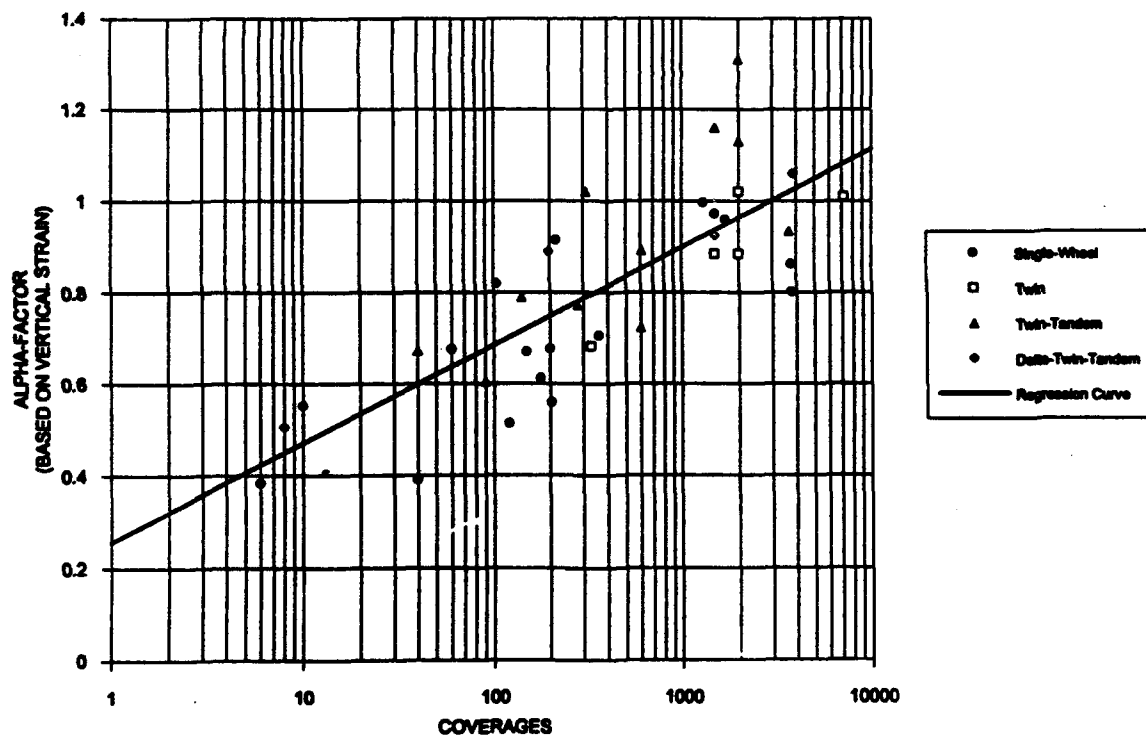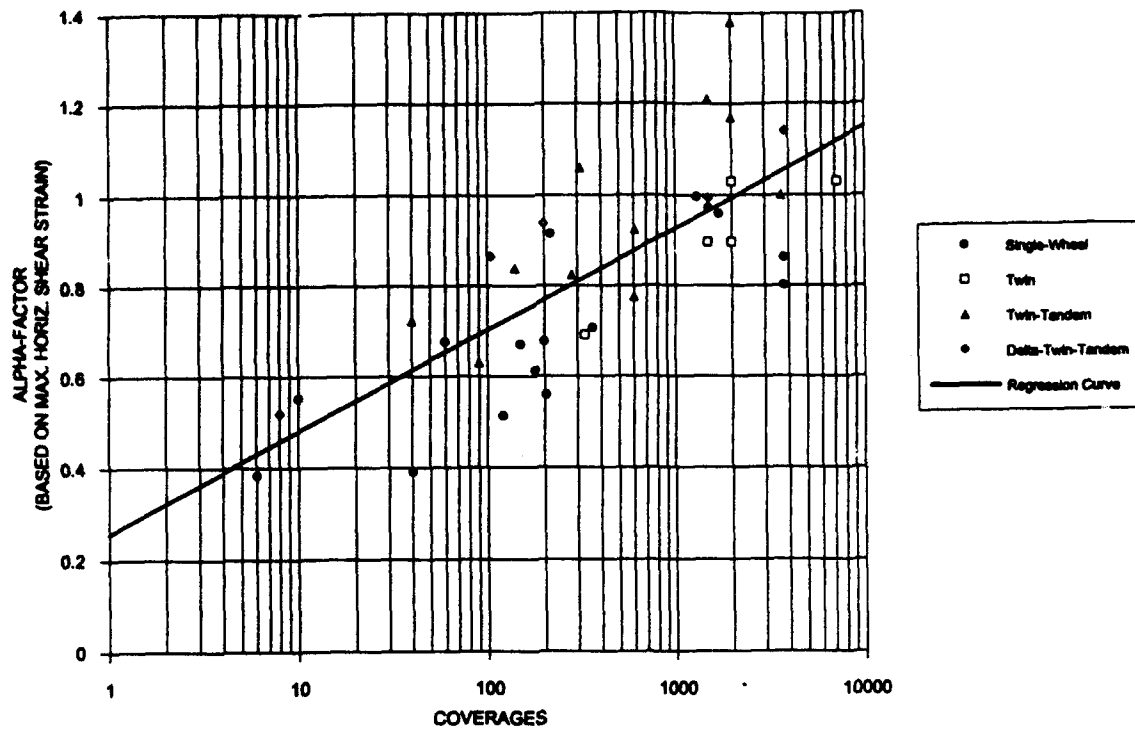**Figure 10.** Plot for the α-curve criteria based on vertical strain

16

Figure 11. Plot for the α-curve criteria based on maximum horizontal strain
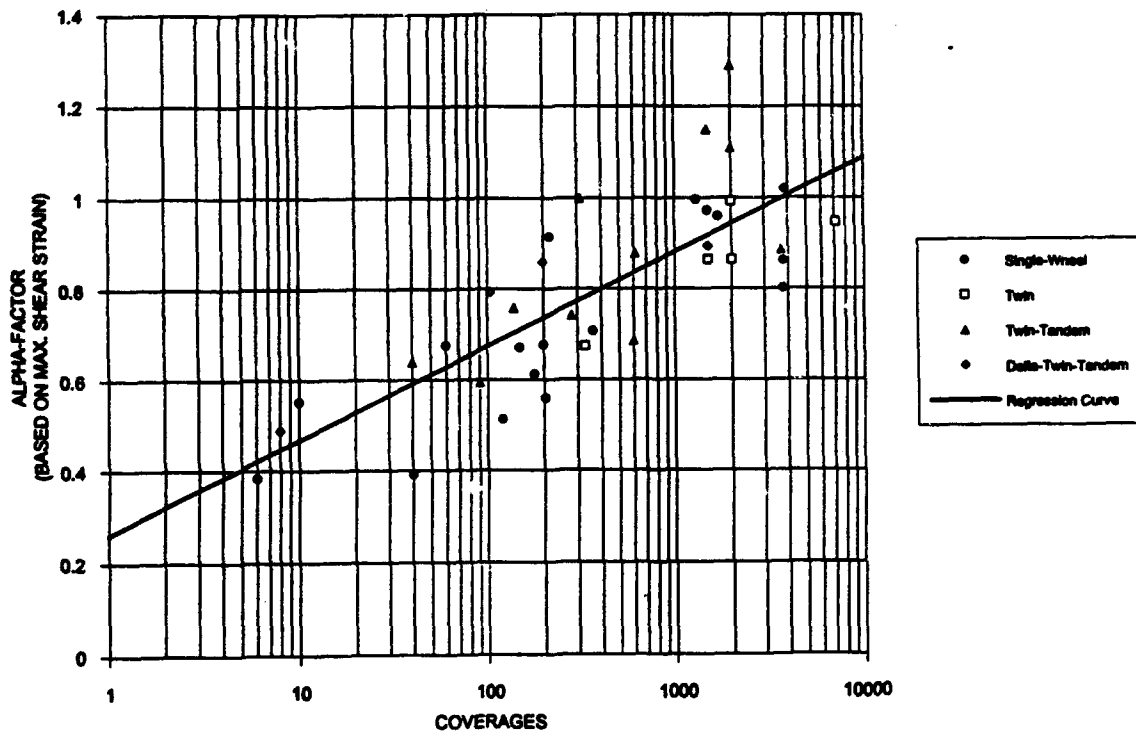

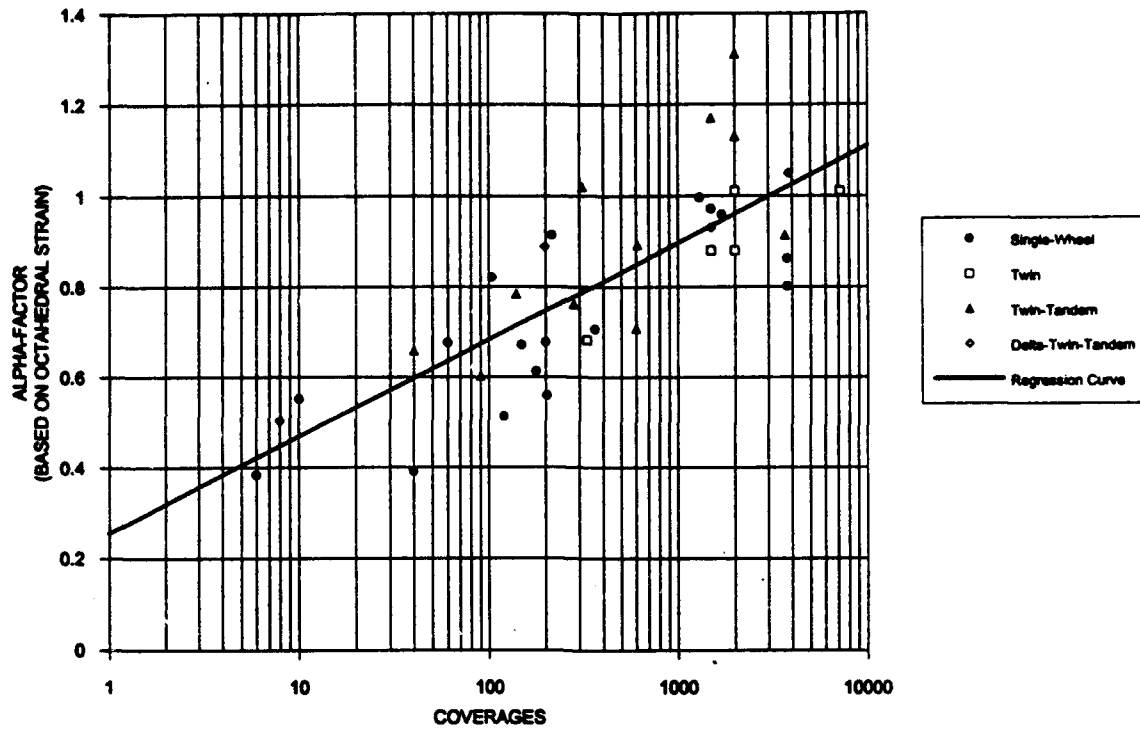**Figure 12.** Plot for the α-curve criteria based on maximum shear strain

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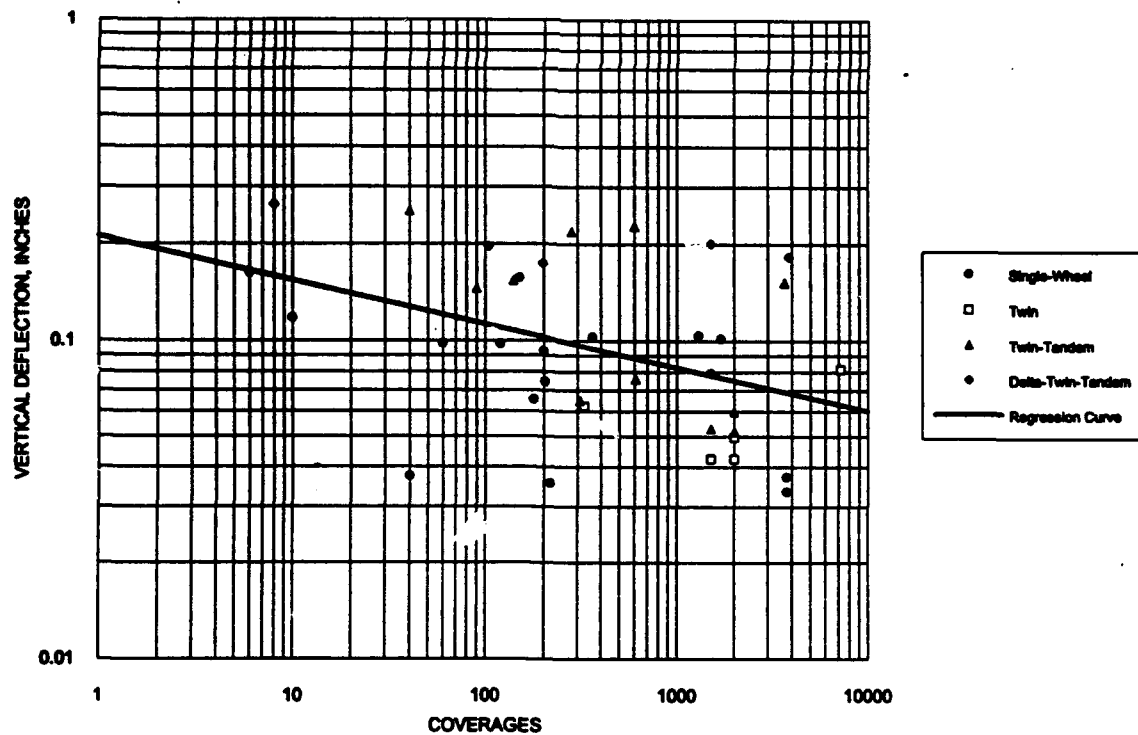Figure 13.   Plot for the α-curve criteria based on octahedral strain

Figure 14.   Performance criteria for multilayer system based on
vertical deflection

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Table 2

Results of the Analysis Performed on the Test Section Data

| Test Point	Thickness Above Subgrade (in)	CBR	Coverages to Failure	Multi-Layer System Analysis					Single-Layer System Analysis				
				Vertical Deflection	Vertical Strain	Max. Horiz. Strain	Max. Shear Strain	Octahedral Strain	Vertical Deflection	Vertical Strain	Max. Horiz. Strain	Max. Shear Strain	Octahedral Strain
1	39.0	8.0	180	0.1570	0.00232	0.00138	0.00328	0.00309	0.2370	0.00463	0.00430	0.00695	0.00695
2	44.0	8.0	1,700	0.1020	0.00146	0.00085	0.00306	0.00194	0.1440	0.00283	0.00238	0.00394	0.00373
3	18.0	18.0	10	0.1180	0.00249	0.00120	0.00333	0.00314	0.1410	0.00315	0.00349	0.00473	0.00446
4	20.5	18.0	60	0.0979	0.00214	0.00114	0.00294	0.00277	0.1180	0.00269	0.00283	0.00404	0.00381
5	23.5	15.5	380	0.1030	0.00213	0.00116	0.00295	0.00278	0.1290	0.00292	0.00292	0.00438	0.00413
6	30.0	17.5	1,500	0.0791	0.00181	0.00094	0.00210	0.00198	0.0960	0.00213	0.00202	0.00350	0.00330
7	48.0	8.0	1,300	0.1040	0.00138	0.00091	0.00195	0.00183	0.1480	0.00283	0.00225	0.00379	0.00357
8	10.0	8.0	3,700	0.0372	0.00193	0.00104	0.00297	0.00251	0.0445	0.00248	0.00244	0.00372	0.00360
9	10.0	9.0	3,760	0.0315	0.00174	0.00094	0.00241	0.00227	0.0098	0.00220	0.00217	0.00330	0.00311
10	15.0	3.7	6	0.1630	0.00599	0.00346	0.00346	0.00795	0.2430	0.01150	0.01043	0.01730	0.01630
11	24.0	4.4	200	0.0928	0.00252	0.00148	0.00386	0.00386	0.1400	0.00304	0.00438	0.00756	0.00713
12	18.0	3.7	120	0.0976	0.00359	0.00207	0.00506	0.00477	0.1460	0.00360	0.00628	0.01050	0.00976
13	12.0	14.0	216	0.0356	0.00167	0.00111	0.00235	0.00232	0.0483	0.00278	0.00282	0.00417	0.00393
14	12.0	7.0	178	0.0483	0.00311	0.00179	0.00438	0.00413	0.0927	0.00564	0.00563	0.00894	0.00794
15	12.0	6.0	303	0.0748	0.00361	0.00202	0.00484	0.00465	0.1060	0.00568	0.00667	0.00973	0.00917
16	5.0	8.0	40	0.0374	0.00169	0.00087	0.00281	0.00236	0.0722	0.00469	0.00653	0.01050	0.00944
17	10.0	27.0	1,500	0.0425	0.00163	0.00079	0.00217	0.00199	0.0446	0.00184	0.00200	0.00316	0.00295
18	10.0	35.0	2,000	0.0425	0.00163	0.00079	0.00217	0.00199	0.0446	0.00184	0.00200	0.00316	0.00290
19	10.0	35.0	228	0.0422	0.00248	0.00131	0.00351	0.00325	0.0693	0.00315	0.00213	0.00311	0.00450
20	15.0	24.0	2,000	0.0497	0.00163	0.00084	0.00222	0.00203	0.0568	0.00214	0.00213	0.00336	0.00308
21	25.0	14.0	7,188	0.0814	0.00142	0.00090	0.00235	0.00190	0.0923	0.00228	0.00233	0.00370	0.00351
22	33.0	4.0	40	0.2550	0.00242	0.00127	0.00380	0.00338	0.2970	0.00388	0.00448	0.00637	0.00581
23	41.0	4.0	280	0.2160	0.00187	0.00099	0.00286	0.00256	0.2720	0.00390	0.00349	0.00464	0.00427
24	14.0	20.0	2,000	0.0919	0.00126	0.00097	0.00181	0.00164	0.0659	0.00172	0.00179	0.00298	0.00246
25	14.0	18.0	610	0.0790	0.00160	0.00094	0.00259	0.00237	0.0924	0.00240	0.00260	0.00398	0.00365
26	20.0	27.0	2,000	0.0600	0.00103	0.00064	0.00190	0.00158	0.0641	0.00143	0.00165	0.00237	0.00207
27	18.0	18.0	1,500	0.0629	0.00124	0.00096	0.00178	0.00163	0.0562	0.00184	0.00184	0.00227	0.00264
28	18.0	5.0	90	0.1440	0.00294	0.00169	0.00428	0.00393	0.1780	0.00564	0.00564	0.00673	0.00751
29	18.0	12.0	310	0.0960	0.00147	0.00090	0.00212	0.00196	0.0727	0.00231	0.00231	0.00364	0.00405
30	24.0	8.0	140	0.1540	0.00169	0.00106	0.00302	0.00269	0.1740	0.00331	0.00369	0.00639	0.00485
31	33.0	5.8	3,660	0.1524	0.00161	0.00079	0.00238	0.00211	0.1730	0.00228	0.00289	0.00373	0.00340
32	33.0	4.4	600	0.2371	0.00221	0.00116	0.00348	0.00308	0.2840	0.00348	0.00411	0.00670	0.00530
33	18.0	3.7	8	0.2640	0.00398	0.00204	0.00650	0.00492	0.2930	0.00401	0.00401	0.01060	0.00598
34	24.0	4.4	104	0.1960	0.00180	0.00097	0.00270	0.00240	0.2120	0.00294	0.00320	0.00488	0.00430
35	33.0	3.3	1,500	0.2010	0.00137	0.00072	0.00207	0.00182	0.2170	0.00309	0.00240	0.00390	0.00318
36	41.0	4.0	3,850	0.1830	0.00105	0.00055	0.00160	0.00142	0.1998	0.00189	0.00184	0.00272	0.00298
37	24.0	5.0	188	0.1756	0.00182	0.00097	0.00243	0.00216	0.1870	0.00259	0.00281	0.00429	0.00378
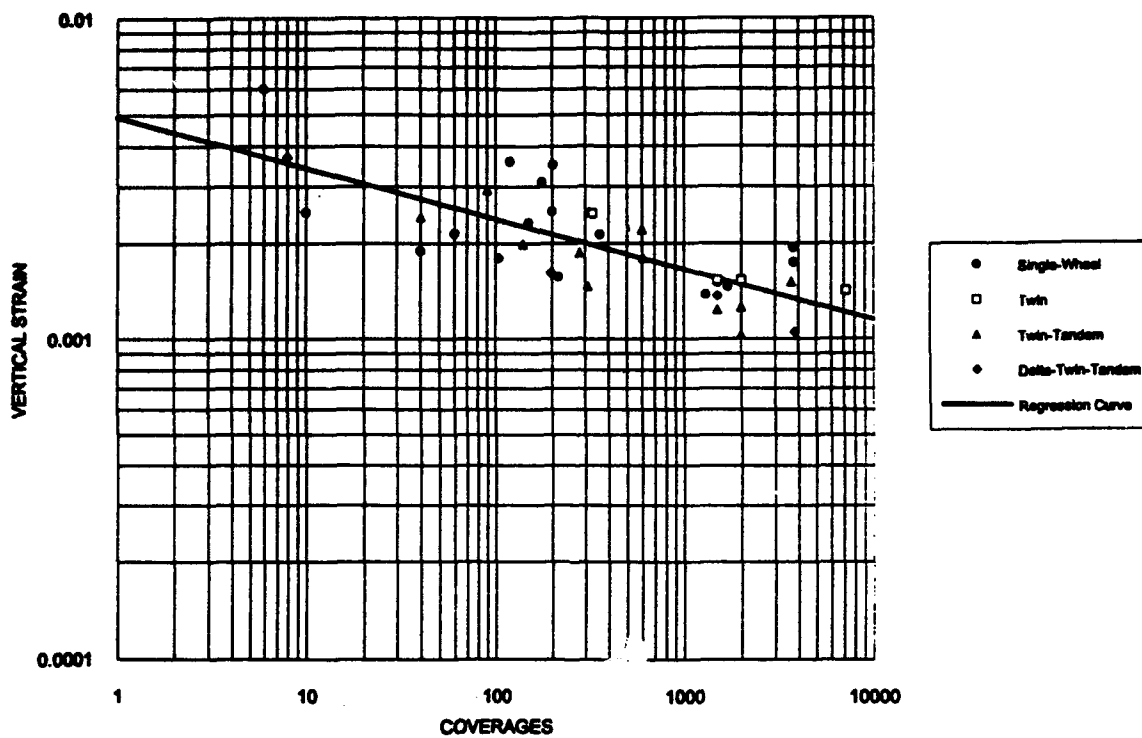
Figure 15. Performance criteria for multilayer system based on
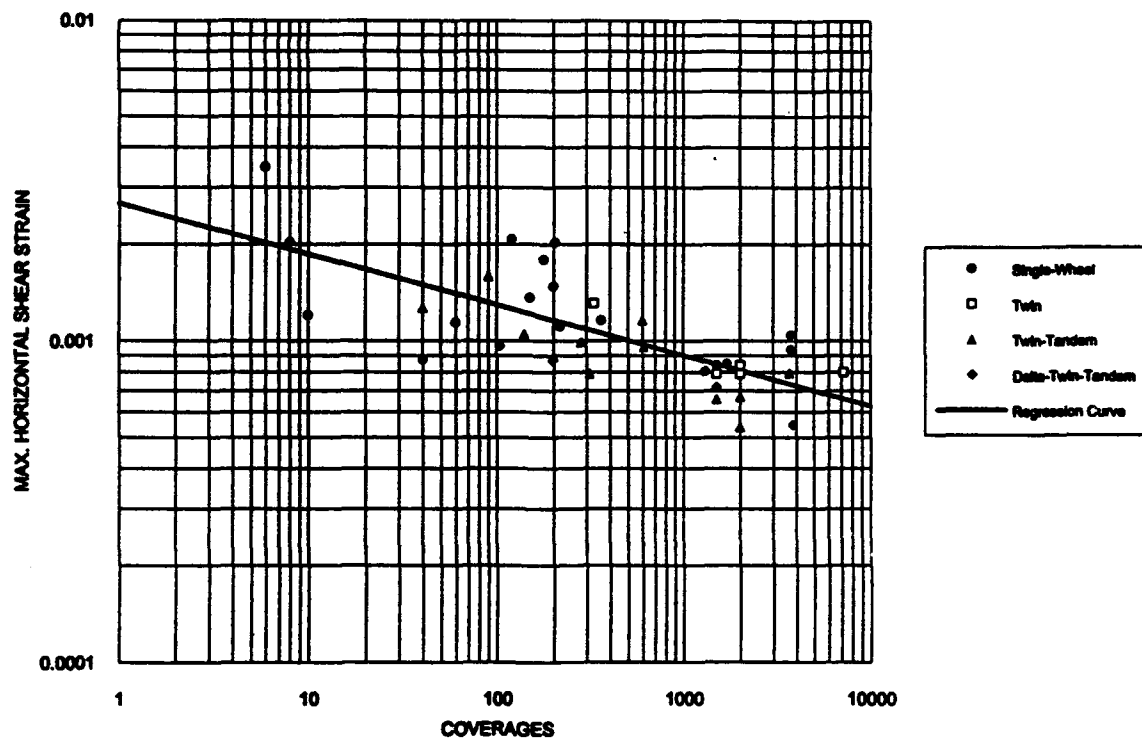vertical strain

Figure 16. Performance criteria for multilayer system based on maximum
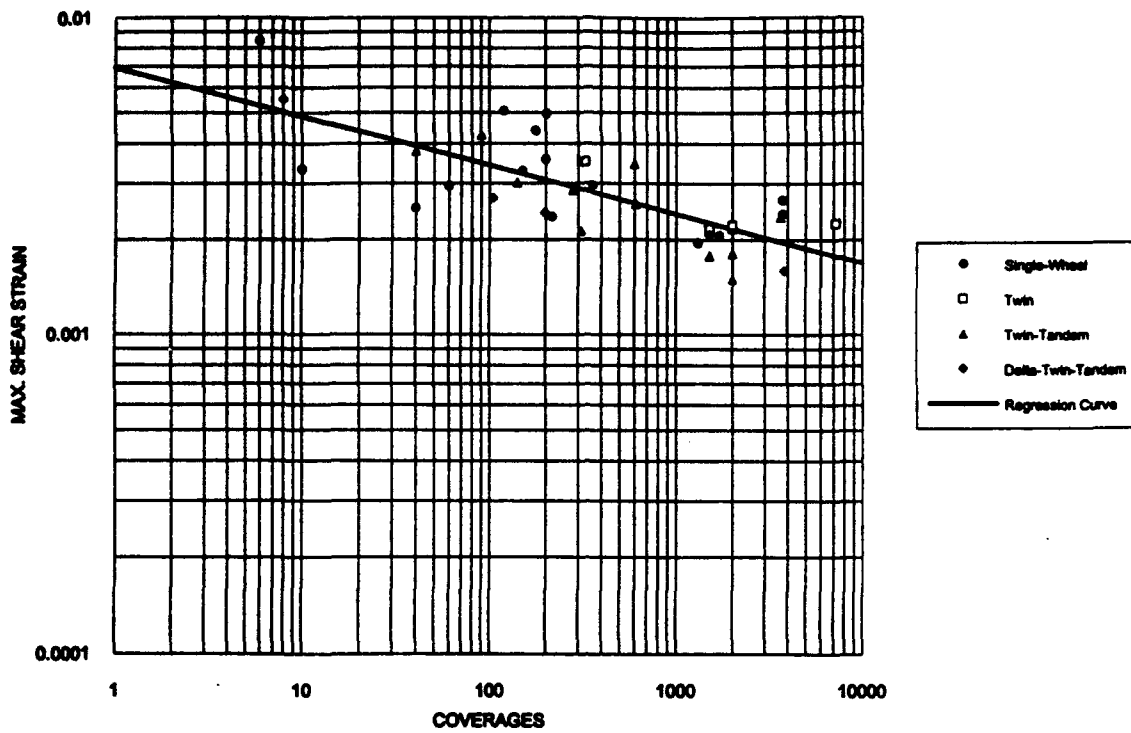horizontal strain

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Figure 17. Performance criteria for multilayer system based on maximum shear strain
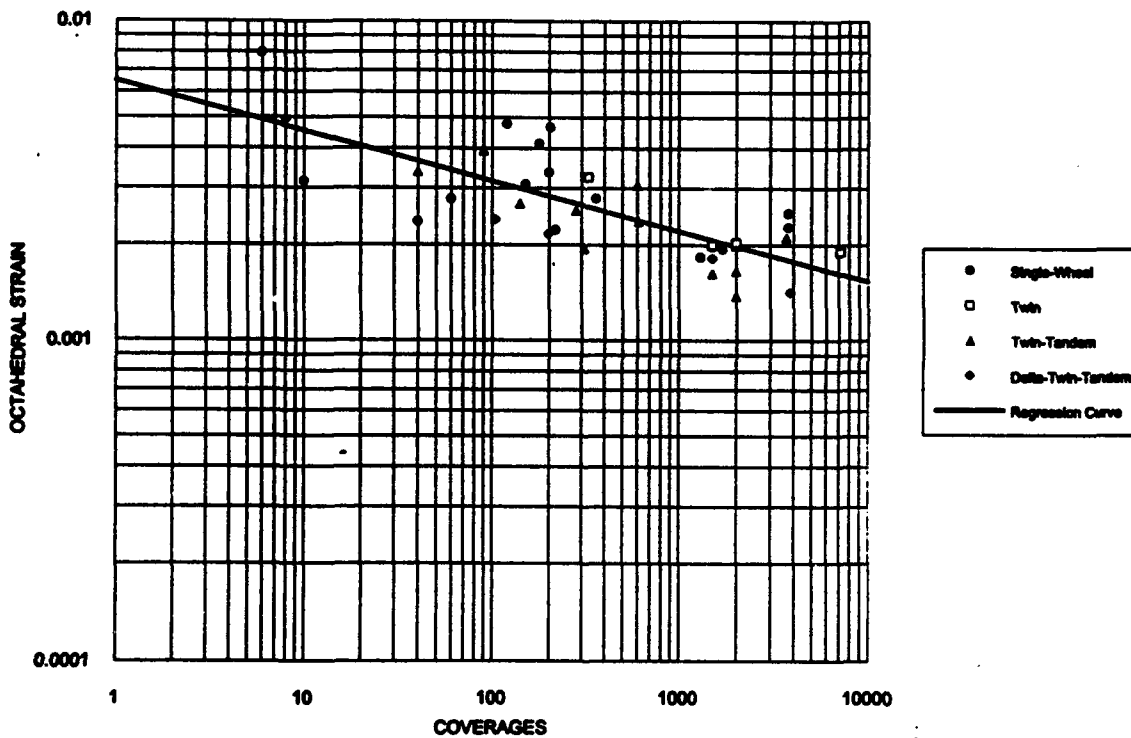

Figure 18. Performance criteria for multilayer system based on octahedral strain
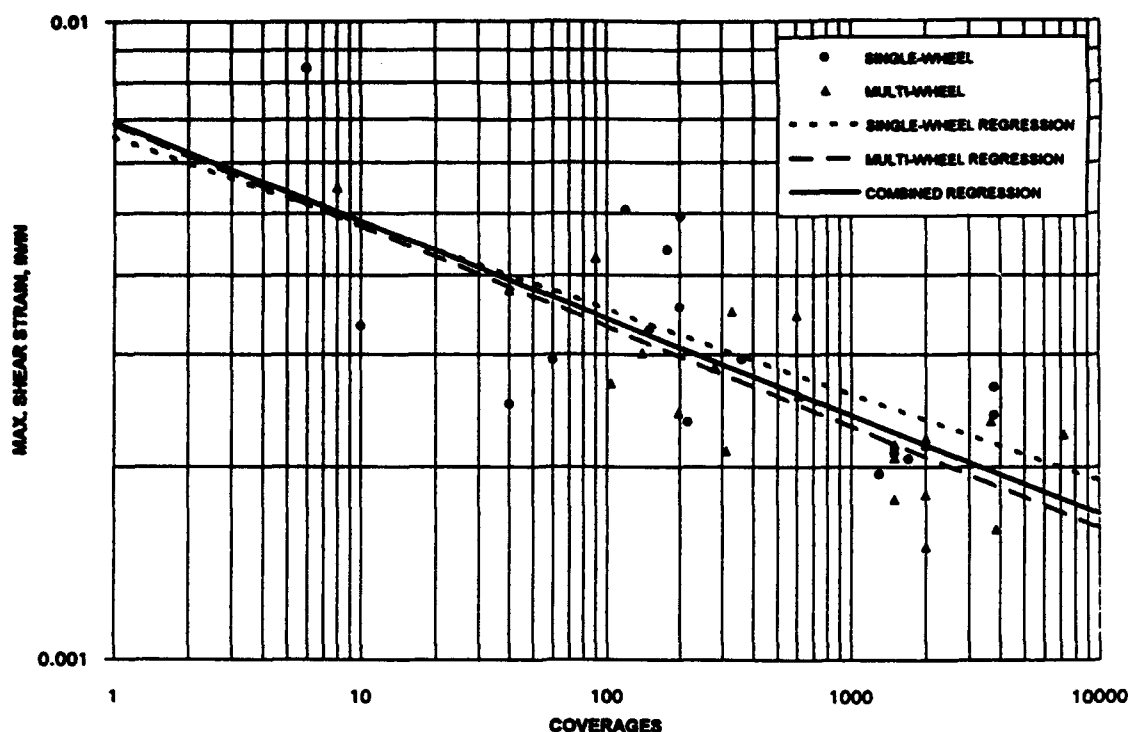
21

Figure 19. Comparison between multiwheel and single-wheel test data

gears are plotted separately. Regression curves were generated for both sets
of data and for the combined data. Considering the overall scatter in the
data, differences between the different regression curves cannot be considered
to be significant.

Selecting a particular strain criteria to be used for design and evalua-
tion appear to be a matter of personal choice. To preclude the elimination of
any of the parameters for criteria, each of the regression curves have been
included in the ACNLEA computer program and are available for pavement
research. The criteria based on maximum shear strain was selected for the
additional comparisons reported later in this report. Maximum shear strain
was selected because of the relationship between pavement rutting and shear.

Performance criteria based on vertical strain had been previously
developed[8] for use with layered elastic criteria. The criteria in this
earlier study was developed to fit closely the current CBR design procedure.
The development of these criteria resulted in vertical strain criteria that
were a function of the subgrade strength. Figure 20 presents a comparison of
the vertical strain criteria developed in the earlier study with the vertical
strain criteria developed in this current study. It becomes obvious that the
new strain criteria, independent of subgrade strength, are very close to ear-
lier criteria for weaker subgrades. For high-strength subgrades, the allow-
able strains determined from the new criteria will be less than the allowable
strains determined from the earlier criteria. For low-strength subgrades, the
design pavement thicknesses should be about the same for both criteria, but
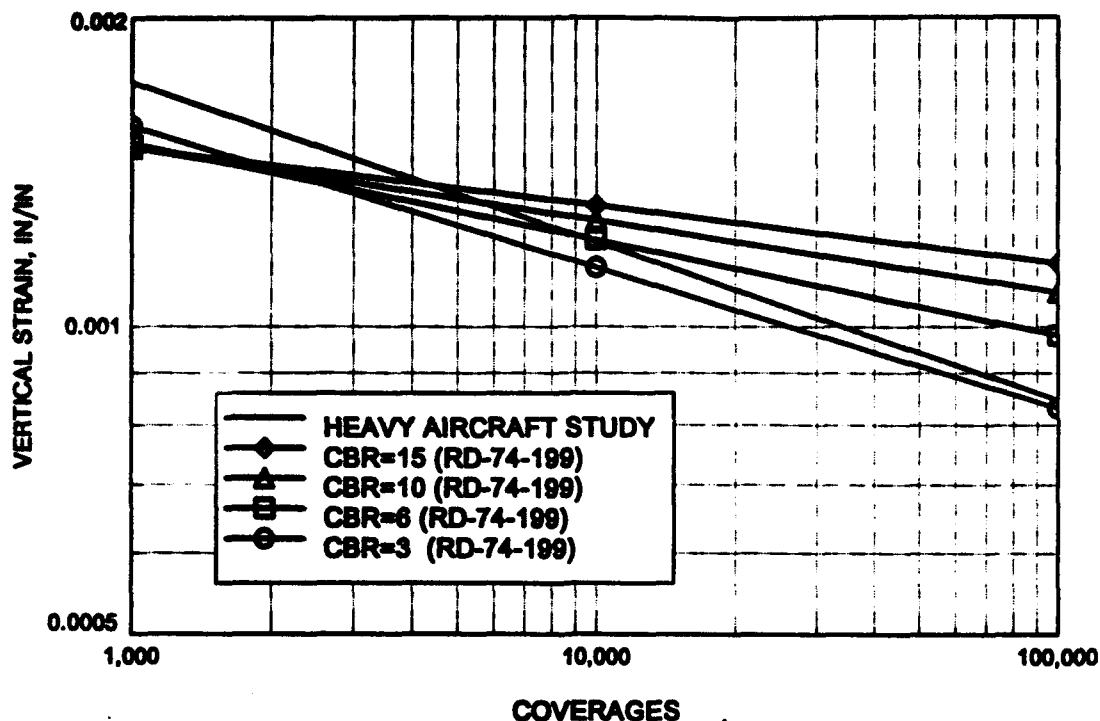
22

Figure 20. Comparison between vertical strain criteria from previous studies and the vertical strain criteria develop in this study

for high-strength subgrades the thicknesses determined using the new criteria will be greater than the thicknesses determined using the older criteria. Since the older strain criteria were developed to produce thicknesses that match the CBR design procedure, the comparison of the new strain criteria and older strain criteria would also apply to a comparison of the new strain criteria and the CBR design procedure.

SINGLE-LAYER ANALYSIS

A similar strain analysis was performed using a single layer to model the pavement structure. The analysis would correspond to a Boussinessq analysis except that a stiff layer was placed at 240 inches. The modulus of elasticity of the subgrade was set at 1,500 times the CBR, and the Poisson's ratio was set at 0.5 (as in the case for the Boussinessq analysis). In the single-layer pavement system, the modulus of elasticity and Poisson's ratio values for the layers composing a pavement structure are assumed to be equal to the modulus of elasticity and Poisson's ratio of the subgrade, respectively. The data from the single-layer analysis are given in Table 2. Figure 21 presents the plot of the maximum shear strain as a function of coverages. The plots of the other strain parameters indicated the same trends. It can be noticed, by comparing data for multiwheel analysis (Figure 16) with the data presented for the single-layer analysis (Figure 21), that both plots indicate a similar correlation of strain with coverages. The regression line in the case of the single-layer system plots above the line corresponding to the multilayer system, but the scatter of the data points is about the same. There is no
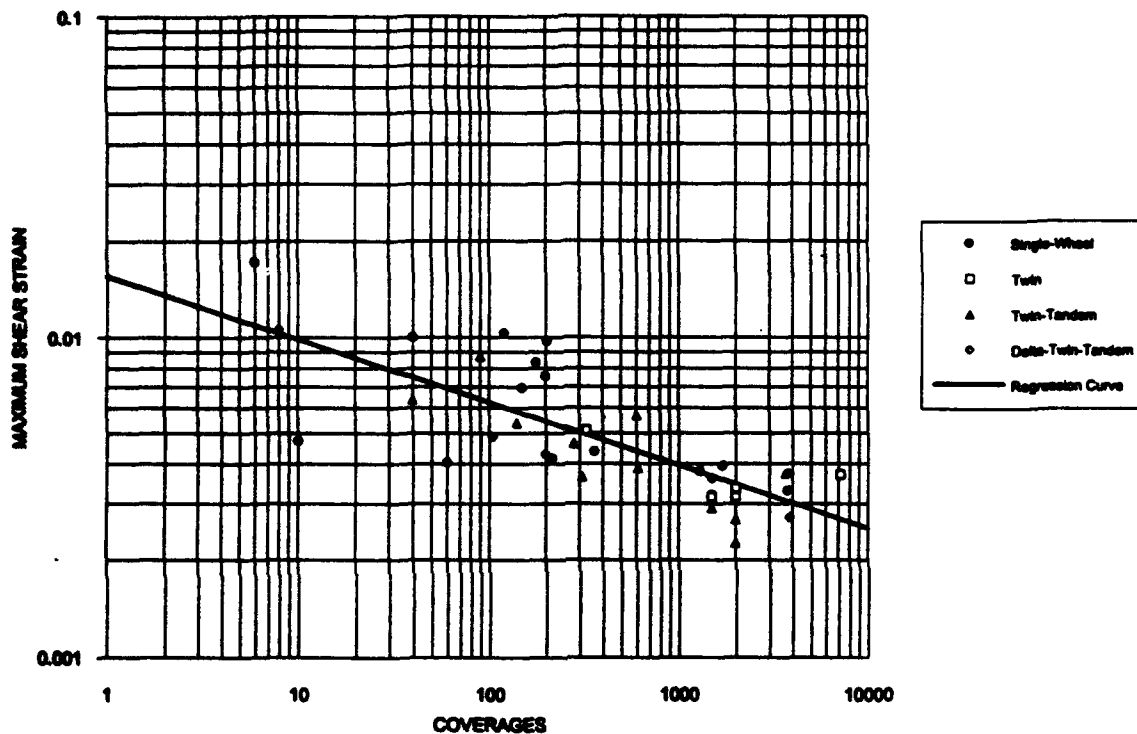
23

Figure 21. Performance criteria for single-layer system based on
maximum shear strain

compelling evidence in the analysis of these data to select one modeling
system over the other. The computer program ACNLEA has the capability of
modeling a pavement using both systems and has the performance criteria for
both modeling systems.

COMPARISON OF DESIGN PROCEDURES

BASIS OF DESIGN COMPARISONS

Design comparisons between the new criteria and other existing design procedures were made. For these comparisons, hypothetical sections of typical flexible pavements were designed from the current CBR design procedure. The layered system for the elastic multilayer design consisted of an AC layer, a granular base layer, a series of subbase layers (depending on the thickness of the pavement), and the subgrade layer. As shown in Figure 22, the thickness of the AC layers was set to 15 percent of the total thickness, the thickness of base layers equal to 20 percent of the total thickness, and a subbase layer equal to 65 percent of the total thickness. For the single-layer system, an AC layer equal to 15 percent of the total thickness was used in the analysis. Four different subgrade strengths were selected based on CBR values of 3, 6, 10, and 15.

Design comparisons were made between the multilayer system, single-layer system, Preston's slope method, and the current CBR design procedure. Comparisons were made for a 43.5-kip single wheel, a B-727 gear (2 tires), a B-747 gear (16 tires), and a proposed landing gear (24 tires) that would support an aircraft of over 1 million pounds. All of the comparisons were made for 10,000 coverages of these gears.

DETERMINATION OF REQUIRED THICKNESS FOR THE ELASTIC LAYER PROCEDURE

To determine the design pavement thickness using the elastic layer procedure, several thicknesses were assumed for the four different subgrade strengths selected. The maximum shear strain is computed at the top of the subgrade for each of the assumed pavement sections, and plots similar to the plots shown in Figure 23 are generated. From this figure, the design thickness can be determined by drawing a horizontal line corresponding to the limiting strain value obtained from criteria plots (Figures 17 and 21) at 10,000 coverages and reading the thickness for each subgrade strength value (Figure 23).

DESIGN COMPARISONS

Figures 24 and 25 show plots for the required thicknesses obtained for a 43.5-kip single-wheel load and the B-727 gear, respectively. Each curve in the plots illustrates the variation in thickness with subgrade CBR for the respective design procedures. These two plots show two general trends occurring in gears with few tires. First, Preston's slope method and the Corps of Engineers procedure tends to agree across the range of CBR values with thicknesses for the latter being slightly larger. Second, for CBR values of 4 and above, the multilayer and single-layer systems give thicker pavements than the Corps of Engineers or Preston's slope methods. For CBR values below 4, the multilayer approach results in thinner pavements than those obtained by the single-layer system. This is because credit given to the structural layers in the multilayer system results in lower strain values. For high CBR values, the two curves converge and give approximately the same results.

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MULTI-LAYER SYSTEM

ASPHALT = 0.15 T	E1 = 250,000 psi, υ=0.5
BASE = 0.20 T	E2, υ=0.3
SUBBASE1	E3, υ=0.3
SUBBASE2	E4, υ=0.3
SUBBASE3	E5, υ=0.3
SUBGRADE	E=1500*CBR, υ=0.4

Figure 22.   Standard pavement sections

Figure 23.   Determination of required thicknesses for the elastic layer design procedure

GEAR1-SINGLE WHEEL (43.5KIPS), COVERAGES=10000

Figure 24. Required thickness versus subgrade CBR for a 43.5-kip single wheel

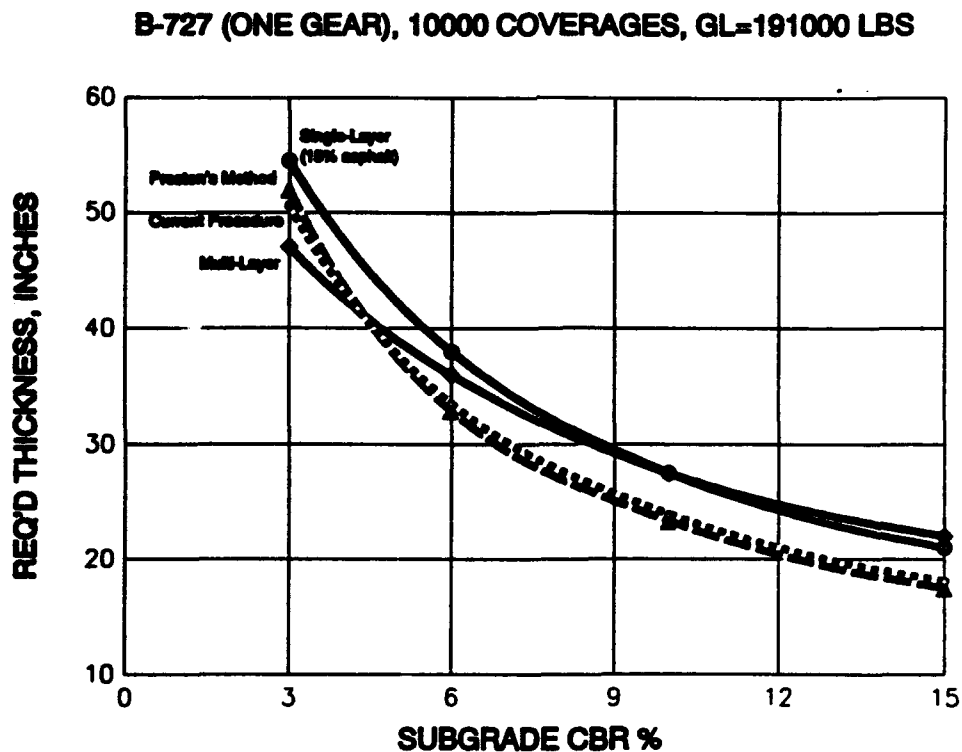**B-727 (ONE GEAR), 10000 COVERAGES, GL=191000 LBS**

Figure 25. Required thickness versus subgrade CBR for a B-727 twin gear

For the case of gears for heavier aircraft with many tires, the result-
ing behavior changes slightly. Figures 26 and 27 illustrate the plots for a
B-747 and a proposed gear intended to support a million pound aircraft,
respectively. It can be noted that the multilayer system consistently gives
thinner sections than the other design procedures. It seems that for heavier
gears with a large number of tires, the Corps of Engineers procedure tends to
overestimate the required thickness, particularly for low strength subgrades.
The exception is the case of high strength subgrade where the curves for the
different procedures get closer together. It can be seen from Figure 27 that
there are considerable reductions in design thickness if the multilayer or
Preston's slope procedures are used for designing pavements on medium- or low-
strength subgrades. This fact may be attributed to the overlapping effect in
the computation of the deflection factors for the equivalent single-wheel load
in the case of the Corps of Engineers procedure. This overlapping effect can
be demonstrated if Figure 27 is compared to Figure 24, where the plots were
generated for a single wheel of the one million pound gear. The difference in
the curves for each procedure corresponds to the influence or overlapping
effect of the tires (and probably the tire arrangement) on the design thick-
ness. It should be noted that for the heavier gears, the thickness of pave-
ment exceeds the greatest thickness in the data base. Also, the comparisons
are for a traffic level of 10,000 coverage, which is far more than the highest
level of traffic for the data base.

EFFECTS OF TIRE SPACING

Additional analyses were performed to assess the effect of tire spacing
on the required thickness of a pavement. The resulting design thicknesses for
twin and twin-tandem gears with various spacings were analyzed for subgrade
CBR values of 3 and 15. The tires in these gears were assumed to have a
50-kip load and contact area of 285 square inches. Thickness comparisons were
made between the maximum shear strain criteria as computed with the multilayer
pavement model and the CBR design procedure.

The analysis was performed by setting a tire spacing and then computing
the applied maximum shear strain at the subgrade level. This strain value was
then used to obtain the design thickness above the subgrade using the criteria
developed for maximum shear strain. The tires in the dual gears were spaced
from 20 inches to 90 inches. For the purpose of this analysis, twin-tandem
gears had a longitudinal spacing between tires equal to 1.25 times the trans-
verse spacing. When the tires transverse spacing was changed, the longitudi-
nal spacing was changed accordingly. Figures 28, 29, and 30 show the results
of the analysis.

Figure 28 illustrates the required thicknesses for twin gears on a sub-
grade with a CBR of 3. The curves on the plot are for the multilayer system
analysis and the CBR design procedure. This plot demonstrates that increasing
the spacing between the tires in a twin gear decreases the required thickness
of a pavement. The decrease in thickness with the increase in tire spacing is
just slightly greater for the layered elastic procedure than for the CBR pro-
cedure. This indicates that greater load attenuation of adjacent tires is
achieved when using the layered elastic procedure. Also shown is signifi-
cantly greater thicknesses required by the CBR procedure.

28

B-747 (16 TIRES), COVERAGES=10000, GL=873000 LBS
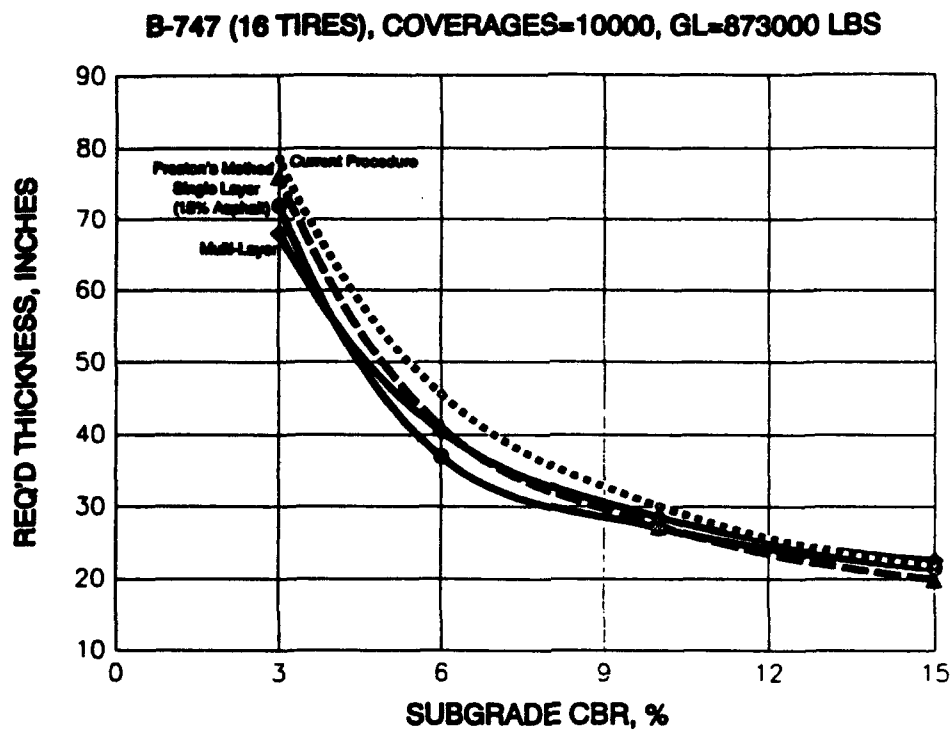
Figure 26. Required thickness versus subgrade CBR for a heavy B-747 gear

GEAR 1 (24 TIRES), COVERAGES=10000, GL=1.1 M POUNDS
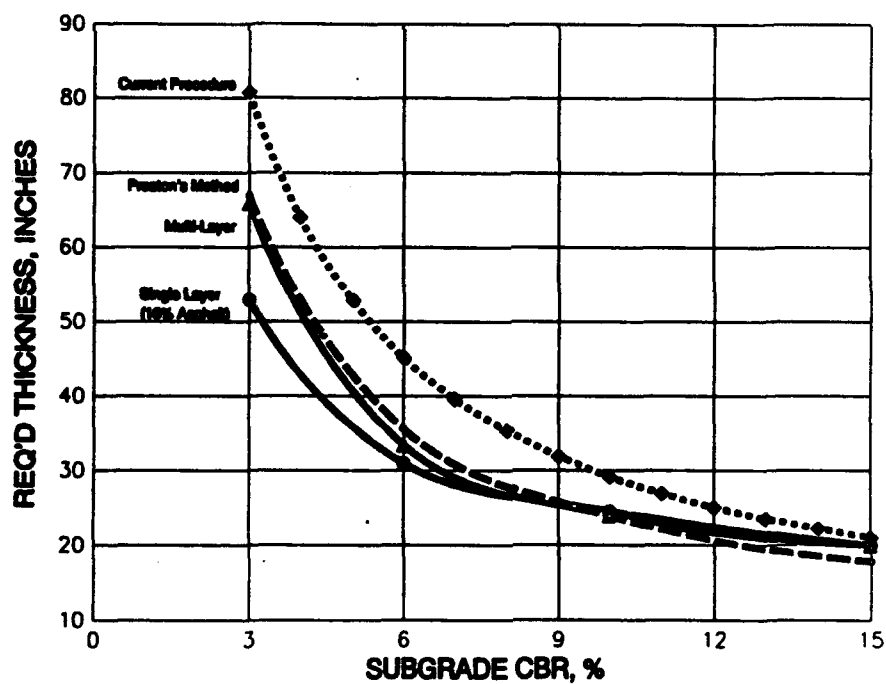
Figure 27. Required thickness versus subgrade CBR for a multiwheel heavy gear

29

TWIN GEAR - VARIABLE SPACING (50 KIPS/TIRE)
CBR = 3 , CONTACT AREA = 285 SQ.IN.
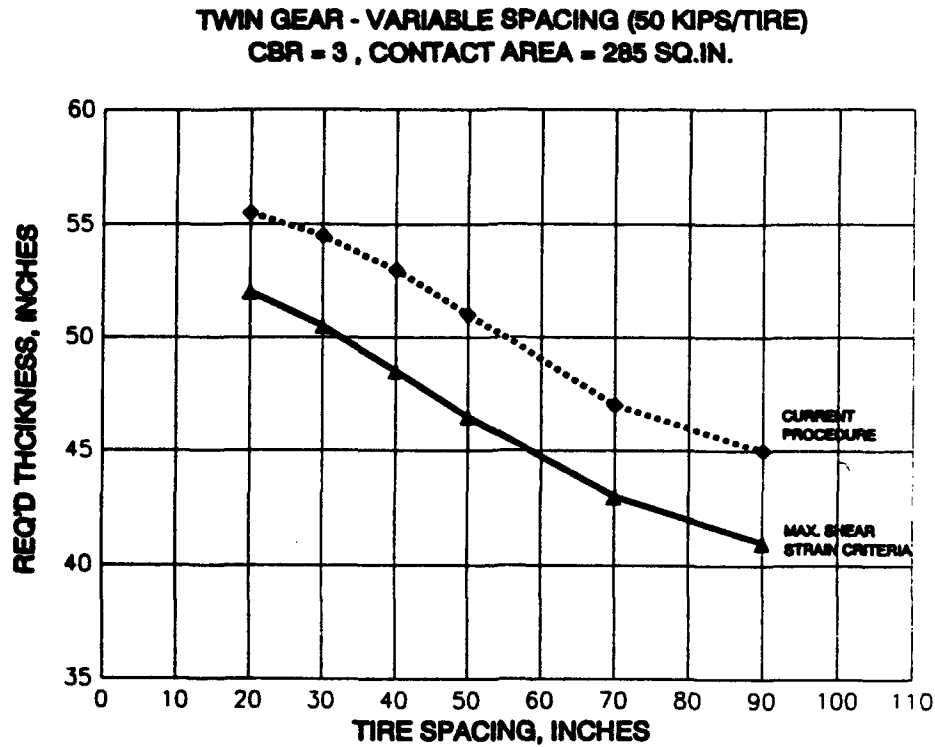
Figure 28. Effect of tire spacing (twin gear, 3 CBR subgrade)

50 KIPS/TIRES, CBR = 3, LONGITUDINAL = 1.25"TRANSVERSE
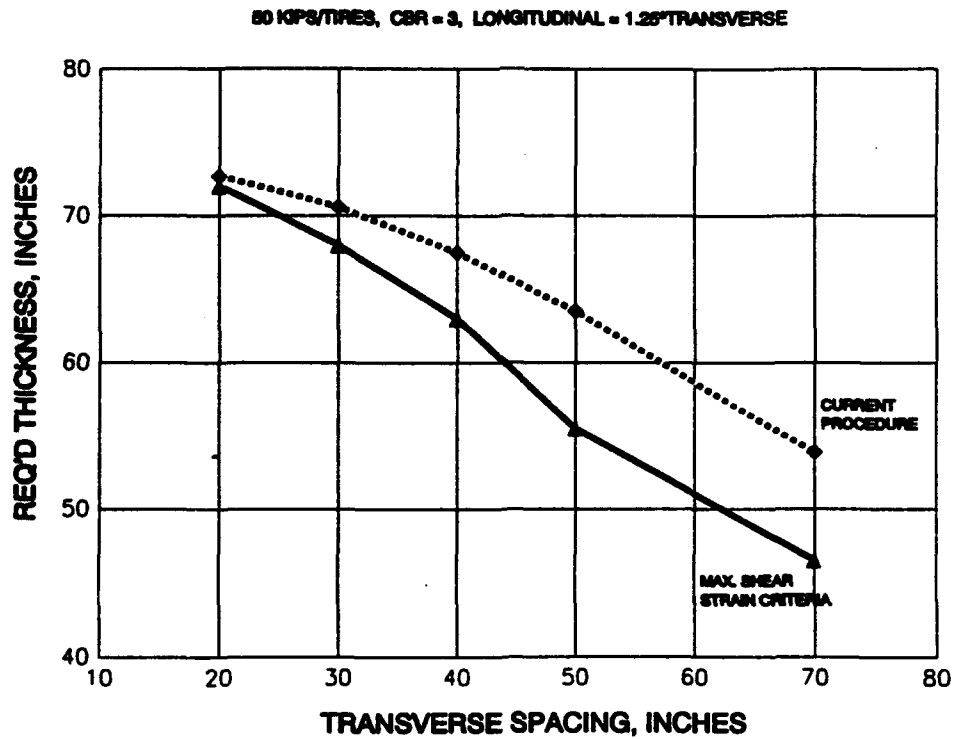
Figure 29. Effect of tire spacing (twin-tandem gear, 3 CBR subgrade)

50 KIPS/TIRE, CBR=15
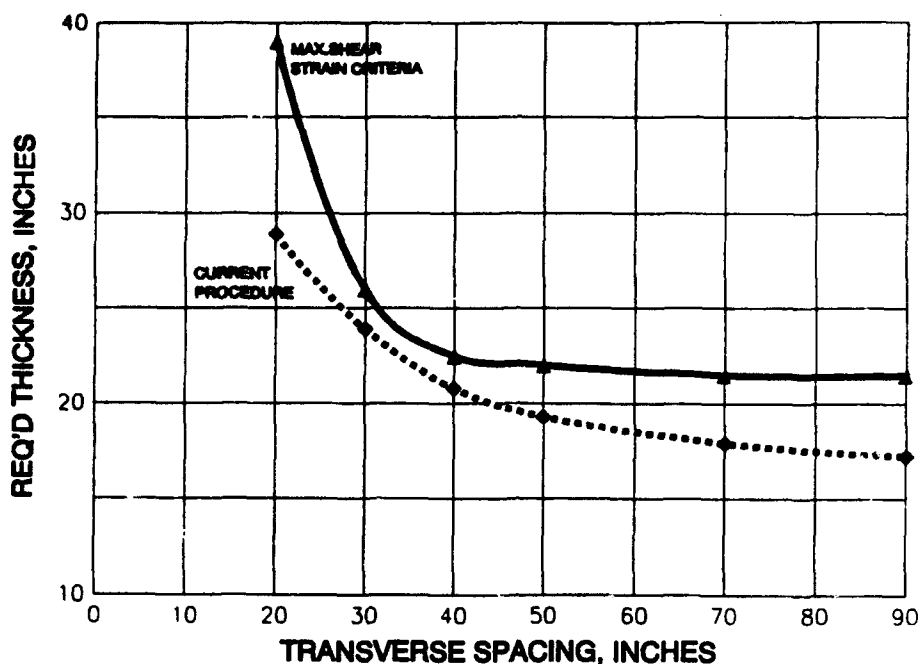
Figure 30. Effect of tire spacing (twin-tandem gear, 15 CBR subgrade)

Figure 29 illustrates the analysis performed for the twin-tandem gear and a 3 CBR subgrade. The load attenuation effects of adjacent tires are more readily apparent for the twin-tandem gear than was the twin gear. As with the twin gear, the CBR design procedure required the thicker pavement at all tire spacings. When the same twin-tandem gear was analyzed for a higher subgrade CBR equal to 15, the behavior changed significantly. Figure 30 shows the required thicknesses for the twin-tandem gear with variable spacing on a 15 CBR subgrade. Figure 30 shows that for tire spacings beyond 40 inches there is no overlapping effect of adjacent tires. For the CBR procedure, there continues to be effect of adjacent tires far beyond the 40 inches spacing. The plot also shows that the CBR design procedure predicts, for the 15 CBR subgrade, slightly thinner pavements than does the strain criteria. For a practical transverse spacing between 30 and 50 inches, the difference between the layered elastic procedure and the CBR procedure is only about 1 to 2 inches.

The comparison performed indicates a basic difference between the CBR design procedure and the layered elastic design procedure as to the effect of tire spacing and the required thickness of aircraft having multiwheel gear. The analysis of data produced performance criteria independent of the number of tires and tire spacing. To develop criteria for the CBR design procedure, the criteria had to be a function of the number of tires. This should also indicate that spacing would be a factor but is not considered. Since the analysis on the data performed by the layered elastic design procedure did produce criteria that are independent of the number and spacing of the tires,

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it is felt that the layered elastic design procedure can be used with a greater degree of confidence when considering the effects of tires on pavement requirements.

DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

DISCUSSION

The analysis of available test data for flexible pavements indicates justification for the suspicion that the deflection-based ESWL is not an appropriate parameter for determining pavement thicknesses for heavy multigear aircraft. Criteria can be developed from strain parameters that describe the pavement performance without resorting to separate thickness adjustment curves for different aircraft gear. Although the maximum shear strain computed on top of the subgrade was chosen for the design parameter, the vertical strain, the horizontal strain, or the octahedral strain could have been chosen. The strain criteria result in a greater attenuation of the overlapping load effects with distance from the load than does the current deflection-based ESWL procedure. The study also indicated some differences between classic CBR-thickness relationship and strain based thickness criteria. Even for single-wheel gear, the classic CBR equation under-predicts thickness for high subgrade CBR values and over-predicts thickness for very low subgrade CBR values, but it compared with strain-based thickness criteria. For multiwheel gears, the differences in load attenuation compensate for the under-prediction but magnify the over-prediction. Since the bounds of the data base are very limited, caution must be exercised in applying the results of the analysis to actual design and evaluation of pavements for heavy multiwheel aircraft. Particularly disconcerting is the extrapolation of the data from a few thousand coverages to hundreds of thousands and from a maximum thickness of 49 inches to thicknesses approaching 100 inches. To illustrate this point, the data for the maximum shear strain criteria were replotted from a log-log plot to an arithmetic plot as shown in Figure 31. When the data are shown in this manner, it becomes apparent that both the data for low coverage levels and the limited data at the higher coverage levels have no clear projection of the relationship between strain and coverage. Extrapolation to thicker pavements may also pose some danger. The premise of the design procedure is that the life of the pavement is increased by reducing the strain at the top of the subgrade. As the thickness of the granular material above the subgrade is increased, an increased portion of the surface rutting and surface cracking can be attributed to the behavior of the granular layers. The worry expressed can only be addressed by having a procedure which considers failure of the pavement as a system failure. For there to be shear in the subgrade, there also must be shear in the asphalt surfacing and granular base layers. To make giant leaps in pavement design methodology, radically new methodologies must be considered. The development of layered elastic design methodology is not the giant leap, but it is a step forward toward improved pavement design methodology. In any case, it will be only through extensive prototype testing and field evaluation that a flexible pavement design procedure can be developed and used with confidence for the design and evaluation of flexible pavements for significantly heavier multiwheel aircraft.

CONCLUSIONS

Based on the analysis of test data presented in this report, the following conclusions have been made:
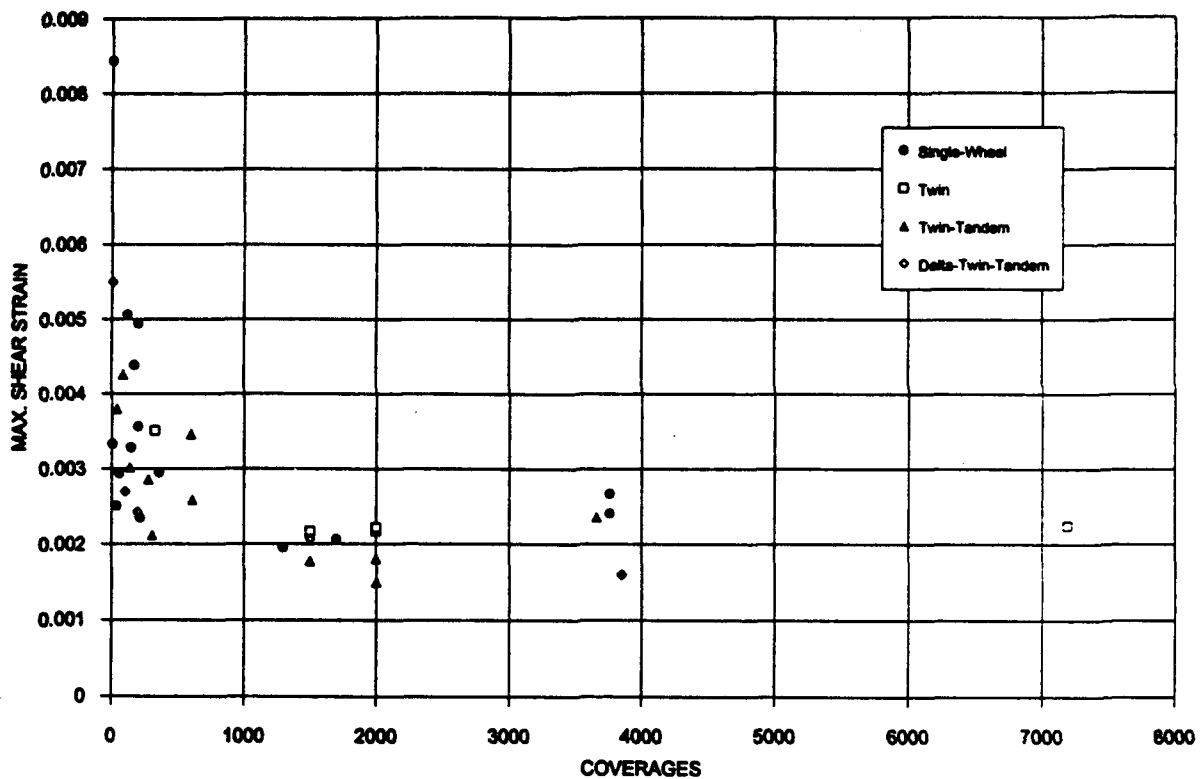
Figure 31. Maximum shear strain criteria plotted in an arithmetic
scale

(1) Criteria suitable for the design of flexible pavements for
multiwheel aircraft have been developed. The criteria are independent of num-
ber of tires and tire spacing.

(2) The degree of confidence in using the new criteria in the design
for flexible pavements for multiwheel aircraft is greater than the degree of
confidence in using the current CBR design procedure. Even for the new crite-
ria the degree of confidence must be considered to be very low. The low
degree of confidence can be attributed to the extrapolation of the data beyond
the bounds of the data and to unexplained scatter in the data.

(3) The use of a layered elastic computational model and a maximum
allowable shear strain criteria (as a factor of coverages) at the top of the
subgrade will result in thinner pavements for subgrades with low CBR values,
but thicker pavements for subgrades with high CBR values. The time-honored
CBR equation relating CBR, load, and thickness appears to be unconservative
for high CBR values.

(4) Overlapping load effects attenuate with distance more rapidly
with the new criteria than with the current CBR procedure. It is possible to
use a distance cutoff with Boussinessq theory to compute ESWL values which
would produce load repetition factors independent of the number of wheels in a
gear. The cutoff distance best fitting the data is approximately 12 radii.

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(5) The strain criteria provide a new way of computing the aircraft classification number which would be superior to current procedure.

RECOMMENDATIONS

As a result of the study, the following recommendations are presented for consideration:

(1) The layered elastic model should be employed for the analysis of flexible pavements subjected to new multiwheel aircraft. The pavement should be modeled using a multilayered pavement system. The performance criteria developed for maximum shear strain should be used to predict pavement performance.

(2) Studies should be undertaken to extend the bounds of the test data and to decrease the scatter of the existing test data. Such studies would involve the construction of full-scale test sections for the testing of multiwheel aircraft gears and studies of existing flexible pavements which have been sustaining a high volume of multiwheel aircraft. Additional analytical studies should be conducted for the existing test sections using new and improved pavement models.

(3) Long term performance studies should be started for newly con- structed flexible pavements. Data bases should be maintained to follow pave- ment performance. For the long term the best performance data will be the performance of actual in service pavements, but such data are the most diffi- cult and expensive to obtain. As an alternative to long term performance studies, performance studies of existing flexible pavements should be under- taken. In such studies flexible pavements which, for structural reasons, are in need of rehabilitation, would be evaluated and the data collected can be used to verify the proposed criteria. In this manner, a large volume of data could be collected at a relatively low cost.

(4) With the adoption of the layered elastic procedure for design of flexible pavements, consideration should be given to changing the method for computing the ACN and the PCN.

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APPENDIX A: USER'S MANUAL FOR THE ACNLEA COMPUTER PROGRAM

INTRODUCTION

Purpose

The ACNLEA computer program was written for the structural analysis of pavement test section data under the project "Super-Heavy Aircraft" sponsored by the Federal Aviation Administration (FAA) and the Air Force. The program's main task is to compute strains, deflection, ACN values, and allowable aircraft loads for given pavement structures subjected to aircraft loadings.

General

The ACNLEA computer program is an analysis tool based on the solution of layered linear elastic half-space pavement structures. It consists of two computer codes to provide data input and analysis of a flexible pavement structure subject to a given loading. The first computer code (ACNIN) is for building of aircraft data files and the second code (ACNHS) is for the input of a pavement section, selecting performance criteria, performing the analytic calculations and obtaining the results. The program will compute the pavement PCN as defined by the equation from the International Civil Aviation Organization (ICAO) manual, the allowable aircraft load based on one or all of five performance criteria, an allowable loading for a single wheel of the aircraft, an allowable loading of a standard wheel, and the aircraft ACN for the allowable loading as determined from the allowable load of the standard single wheel. The performance criteria have been developed from the analysis of 37 test sections. The criteria developed are based on deflections, vertical strains, horizontal strains, maximum shear strains, horizontal shear strain, and octahedral strains computed at the top of the subgrade. The allowable loads listed in the program output for the aircraft, the aircraft single wheel, and the standard single wheel are loads that produce a computed response equal to the allowable response as determined from the criteria. Therefore, all these loads are considered to be equivalent in terms of pavement response parameters. The aircraft ACN presented in the output is the equivalent load for the standard single wheel converted to kilograms then divided by 500. Also presented in the output are the allowable response parameters (deflection or strains), the computed pavement response for the aircraft gear, a single aircraft tire and the standard tire, and the coordinates for horizontal location of critical pavement response.

Aircraft

The program will consider any aircraft in the analysis but only one aircraft at a time. The aircraft data are input through the interactive program (ACNIN) that builds and stores aircraft data files. When the analysis program (ACNHS) is executed, the aircraft to be used for the section analysis is selected from a list of aircraft data files. The basic aircraft data needed are the wheel spacing, aircraft load, wheel load, and either the tire contact pressure or the tire contact area. In building the aircraft data files the standard single-wheel data are automatically added to the data files by the

input program. Also needed is geometrical data to set up a search grid for locating the maximum value for each of the response parameters. Once built the aircraft data files may be retained for future use.

Pavement Section

Two types of pavement sections may be considered for analysis. One type of pavement section is where the pavement is considered to be a single-layer half-space system. In this single-layer analysis the pavement structure is assumed to have the same properties as the subgrade. The other type of pavement section is considered multilayered with each layer having properties as determined by a standard procedure. The section data are input interactive with the execution of the analysis program (ACNHS). Built into the analysis program are performance criteria for both types of pavement sections. The proper criteria are automatically selected depending on the choice of pavement type to be analyzed. The basic data required for input of a pavement section are the structure thickness and the subgrade CBR. The selection is made between the single-layer system or the multilayer system. The properties of the section required for the layered elastic analysis are automatically generated by the program and stored in a temporary data file.

Other Program Data

In addition to selection of the aircraft and pavement section, three other selections are made with the execution of the ACNHS computer program. The first selection is between an analysis based on constant tire contact area or constant contact pressure. The analysis for the constant contact area would be similar to the FAA and Army flexible pavement procedure which uses a constant contact area for determining the equivalent single-wheel load. The constant contact pressure analysis relates to computing aircraft ACN values based on a standard (tire pressure) single wheel. The second selection to be made is the response parameter for the analysis. This selection need only be made for the constant tire contact pressure case. The selection is for one of the five response parameters mentioned previously. For an analysis with a constant tire contact area the analysis is given for all response parameters. The third selection is for a cutoff distance. The cutoff distance is the maximum distance from the center of the tire for which a response parameter will be computed. This is provided because with widely spaced gears, search grid distances may be generated for which the layered elastic program is no longer accurate. The actual cutoff distance used in the program is equal to the thickness of the pavement structure plus the cutoff distance (entered by the user) times the radius of a tire contact area.

BASIC COMPUTER OPERATIONS

COMPUTER REQUIREMENTS

The ACNLEA computer program was coded for IBM compatible personal com-
puters running under the disk operating system (DOS) 3.0 and above. Because
of the math intensive nature of the program, a PC with a fast microprocessor
and a math coprocessor is highly recommended.

To run this program a PC with 500 bytes of free memory is required.
Although not required, a computer with a hard disk subsystem is also recom-
mended, as this will increase program speed and will provide sufficient disk
space for input, output, and temporary files. The program has the option of
using a pointing device (mouse) to make on-screen selection easy to perform.

USER'S MANUAL CONVENTIONS

The following typeface conventions are used to describe the different
features included with the program.

Typeface Convention	Description
(F10)	Instructs the user to press the designated key on the keyboard (in this case the F10 key).
C >	Refers to the DOS prompt.
C > ACN	Instructs a user to type the command at the DOS prompt and then press the (ENTER) key on the keyboard.
[OK]	Refers to an on-screen button or icon that can be selected or "pressed" with a pointing device (in this case the [OK] button).
(UpArrow)	Instructs the user to press the up arrow key on the keyboard.
(DnArrow)	Instructs the user to press the down arrow key on the keyboard.
[CBR=____]	Refers to an input field where the user has the option to type a value.
200000	Indicates to the user to type a field value in an input screen.

DESCRIPTION OF COMPUTER PROGRAMS

MAIN MENU PROGRAM

The ACNIN and ACNHS programs are executed from a control program called ACN, whose only function is to provide a menu for the ACNIN and ACNLEA programs. This program is run by entering: C > ACN at the DOS prompt and press the (ENTER) key. The menu of programs is shown in Figure A1. Pressing the [Input Aircraft Loads] button runs the ACNIN program and pressing the [Compute ACN Values] button runs the ACNHS program. A [Help] button is also provided with a brief description on the options available. To end the program and return to DOS the [Exit to DOS] button is pressed. As an option, the user may execute the ACNIN program or the ACNHS program directly from DOS by typing the executable names at the DOS prompt.

ACNIN INPUT COMPUTER PROGRAM

General

ACNIN is the input program for the aircraft data. This program builds a load data file containing the necessary data for a gear assembly or aircraft. To run the ACNIN program the user can select the [Input Aircraft Loads] button shown in Figure A1 or alternatively type: C > ACNIN. A welcome screen is displayed which can be passed by pressing the (ENTER) key. After passing the welcome screen, the main input screen shown in Figure A2 is displayed. This screen is subdivided into three areas: (1) Aircraft Information, (2) Search Grid Data, and (3) a Push Button Menu at the bottom of the screen.

Aircraft Information

A description of the input fields in this screen area follows (refer to Figure A2). To navigate between the various input fields the (UpArrow), (DnArrow), (ENTER) key may be used. Additionally, the user may click directly in the desired field with a suitable pointing device.

(1) Designation: Enter a brief description of the problem or type of aircraft. The length of the description is limited to the length of the input field itself. For example: B-747 200 Kips. Filling this field is optional.

(2) Gross Load: Enter the gross load (in pounds) of the gear or aircraft to be used in the analysis. For example: the 200,000 in the field (Figure A2) represents the load to be applied to one gear of a B-747 airplane. Filling this field is required.

(3) Fraction of Load on Gear to Analyze: Enter the fraction (not the percent) of the gross load entered in the previous field (Gross Load that acts on the gear to be used in the analysis. For example: 1.0 shown in Figure A2 indicates that all of the 200,000-lbs load is to act on the four tires to be used in the analysis. Filling this field is required.
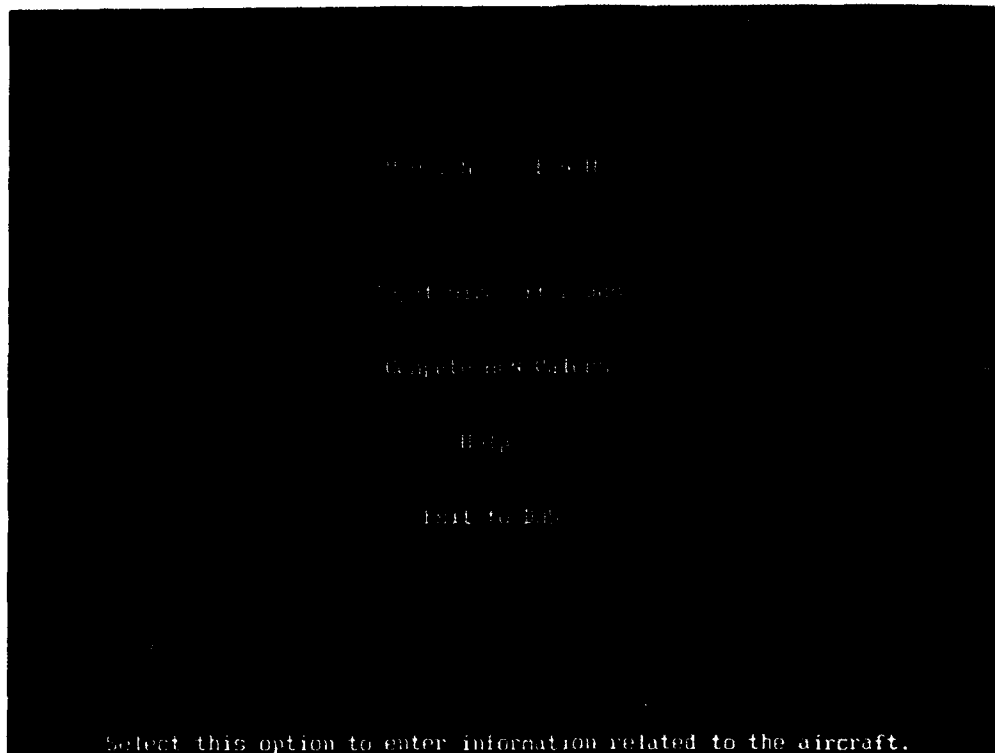
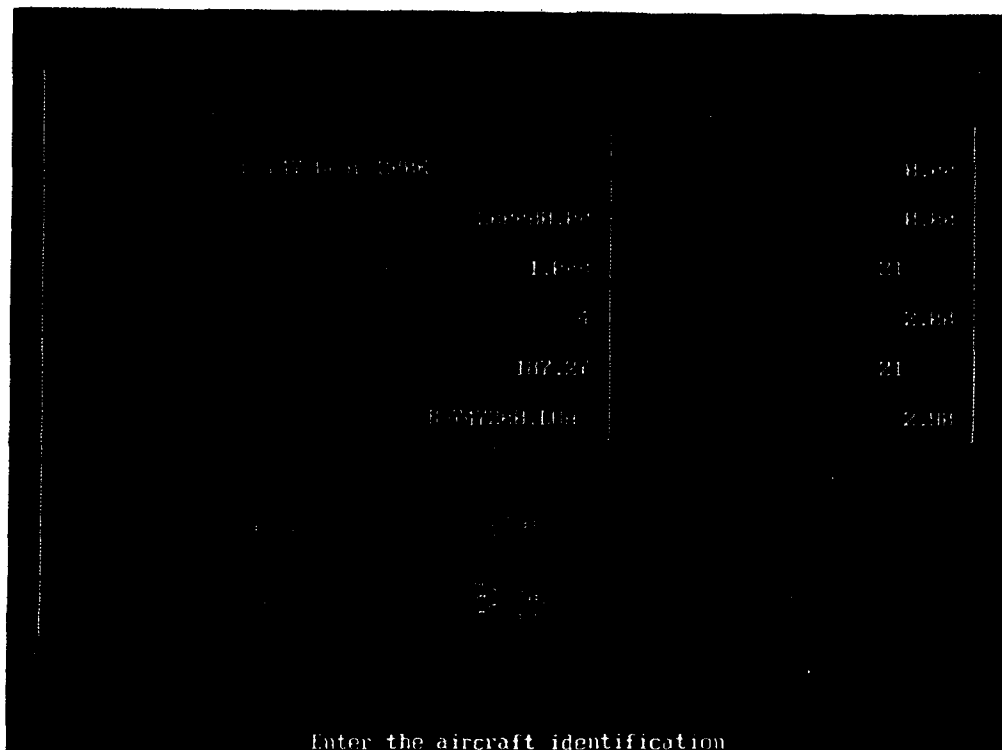A4

Figure A1. Main menu for the ACNLEA computer programs

Figure A2. Input screen for the ACNIN computer program

A5

(4) **Number of Tires:** Enter the number of tires composing the gear to be analyzed. Note that the maximum number of tires is 50. In the example shown in Figure A2, only four tires of the B-747 airplane are to be used in the analysis. Filling this field is required.

(5) **Tire Contact Pressure:** Enter the tire contact pressure (in pounds per square inch) of the tires in the gear assembly. For most design and analysis problems this contact pressure may be assumed to be equal to the tire inflation pressure. Filling this field is required.

(6) **Load Data File Name:** Enter a name for the load data file. This name needs to be a DOS compatible file name, 8 characters for the file name and 3 characters for the file extension (In the example shown in Figure A2 the data file will be named B-747200.LOA). If the file extension is omitted, the LOA extension is used by default. Filling this field is required.

Search Grid Data

The search is used to ensure the determination of the maximum value of the response parameter. Except for the case of the horizontal shear strain, the maximum value can be found if a grid is set up covering the area between the tires. When considering horizontal shear strain, it is important to extend the grid outside the area of the tires.

Because the computer programs are math intensive during the determination of the response parameters, the use of symmetry and fewer nodes in the grid will help reduce the calculation time. For example, in a twin-tandem gear only one-quarter of the gear needs to be searched as is illustrated by Figure A3. The spacing between the nodes in a grid depends on the tire spacing and the degree of accuracy desired. A description of the input fields in this screen area follows:

(1) **X and Y Grid Origin:** This is the location of the grid origin. It describes one of the corners of the search grid rectangle. Filling this field is required.

(2) **Number of Lines in the X and Y directions:** These X and Y values define the number of lines (or nodes) that make up the grid. The more lines entered, the finer the grid will become. The number of lines need not be equal along the X and Y axes (the grid does not need to be symmetric). Filling this field is required.

(3) **Increment in the X and Y directions:** These values are the spacing between the lines (or nodes) in the grid along the X and Y axes, respectively. These increments may be either positive or negative numbers. Positive numbers indicate the grid origin is located at the bottom-left corner of the grid rectangle, and negative numbers indicate the grid origin is located at the upper-right corner of the grid. Fine mesh grids provide better resolution for determining the maximum values of pavement response but require more computer time.
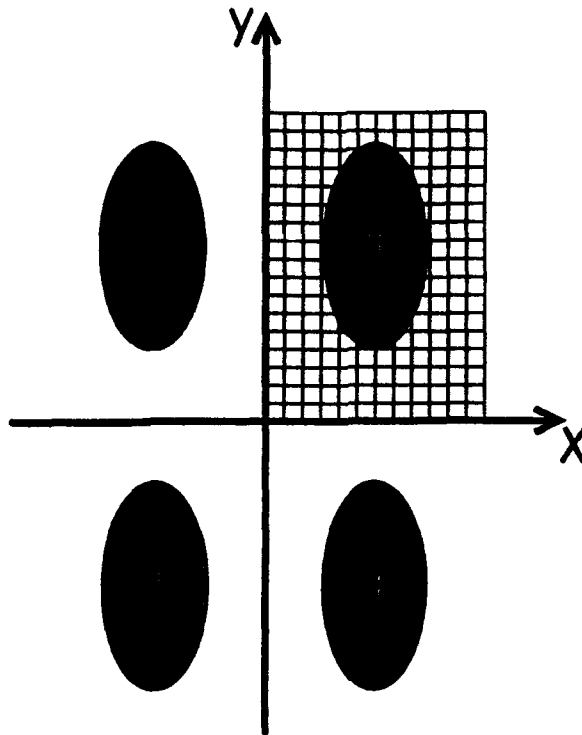
A6

Figure A3.   Search grid for a twin-
tandem gear

On fast personal computers (with fast Intel 80386 and 80486 processors) the increment value can be set to 1 or 2 inches and without creating an unacceptable long run.

Button Menu

(1)   [TIRE COORD.] Button: Click on this button or press the (F2) key to open an input screen for the gear tire coordinates.   Figure A4 presents this input screen that consists of a series of X-Y tire coordinates pairs. The coordinates shown in Figure A3 are for a twin-tandem gear having spacing of 44 inches by 58 inches.

(2)   [LOAD] Button: Click on this button or press the (F3) key to load from disk load data file already built.   A list of available load data files will be presented from which a data file may be selected.

(3)   [SAVE] Button: Click on this button or press the (F4) to save the load data file after finishing entering all data for an aircraft.   The aircraft load data file must be saved in order to use the data entered in the ACNHS computer program.

(4)   [CANCEL] Click on this button or press the (Esc) key to disregard any data entered.   When pressed, the input fields will be re-initialize and the user may type new values.
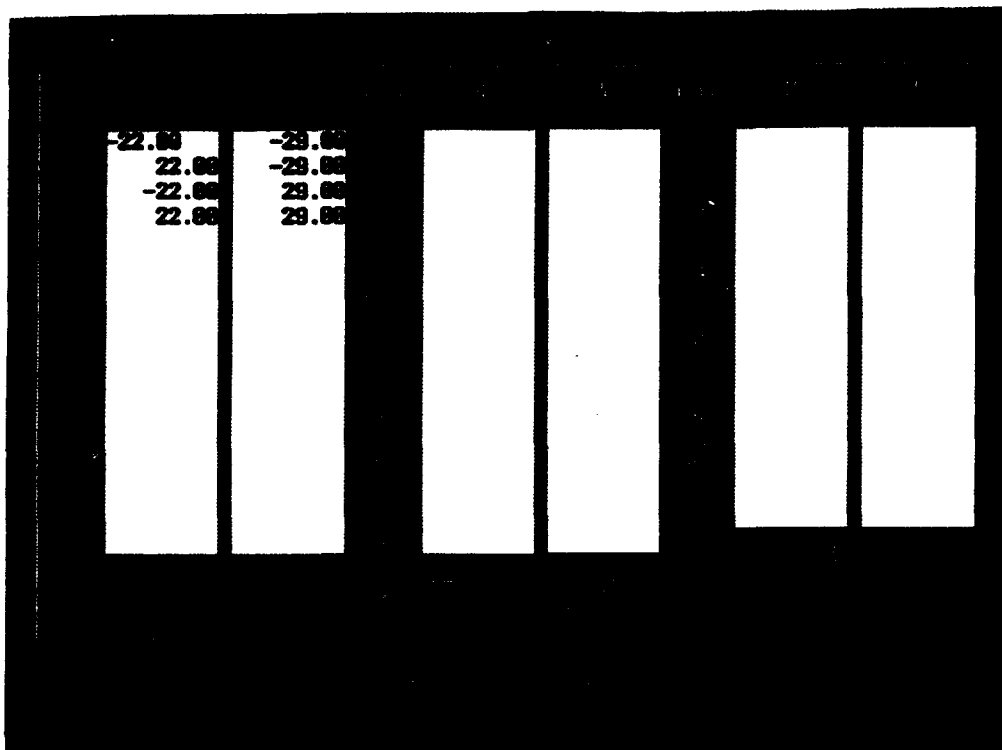
A7

Figure A4. Input screen for the gear tire coordinates

(5) [HELP] Button: Click on this button or press the (F1) key to get an explanation on the input fields of this screen.

(6) [EXIT] Button: Click on this button or press the (F9) key to end this program and return either to the menu of programs or to the DOS prompt.

ACNHS COMPUTER PROGRAM

General

The ACNHS program provides input of the pavement structure, selection of control parameters, computational analysis, and output of data and results. The program is executed by selecting the [Compute ACN Values] button from the main menu of the ACN program as shown in Figure A1 or by typing C > ACNHS at the DOS prompt. After the welcome screen is displayed, a main input screen like the one shown in Figure A5 is presented. This screen consists of a series of input areas defining the method of calculation, type of layer system to use, performance criteria, subgrade strength category, traffic coverage level, pavement section, load data files, response parameter cutoff distance, and a button menu. The various input fields are described in the following paragraphs.

Method of Calculation (ASSUME CONSTANT)

This is the input field described by the ASSUME CONSTANT section in Figure A5. Two methods are available: tire contact area and contact pressure.

A8

Figure A5. ACNHS input screen

When the tire contact area is assumed to be constant, the calculations throughout the computer program are greatly shortened because the relationship between load and pavement response is linear as illustrated in Figure A6a. This means that knowing the load value at a particular response allows the calculation of the allowable load at the allowable response (from the performance criteria) by simply projecting up or down the line. Notice that only one load-strain point defines the line since it must pass through the origin. When the contact area is chosen, it is possible to handle the computations for all criteria in one run of the program. However, when the tire contact pressure is assumed to be constant, the relationship between load and pavement response is not linear as illustrated in Figure A6b. In this case, an iterative procedure must be followed in which a load is assumed and a response is calculated and compared to the allowable response given by a selected performance criteria. If the computer response is different from the allowable response, then a new load is assumed and the procedure repeated until a match is achieved (within a certain tolerance). When the constant pressure is chosen, only one criteria can be considered in one run of the program. To select a calculation method move the cursor to the desired method and press (ENTER) or click on it with a pointing device.

Type of System (LAYER SYSTEM)

     This input allows the selection of either a single-layer pavement system or a multilayer pavement system. The performance criteria in terms of strains values and deflections will be selected for either the single-layer or multi-layer pavement structures. In the single-layer pavement system, the modulus

A9

of elasticity and Poisson's ratio values for the layers composing a pavement structure are assumed to be equal to the modulus of elasticity and Poisson's ratio of the subgrade, respectively. The subgrade modulus is estimated by the relationship: $E = 1,500$ CBR, where E is the modulus of elasticity and CBR is the subgrade strength index (see ASTM 4429, MIL-STD-621A). In the multilayer pavement system, appropriate values for the modulus and Poisson's ratio are assigned to each individual layer. In this manner, the strength characteristics of the various layers can be taken into account more rationally. The computer program automatically assigns appropriate modulus and Poisson's ratio values to the various layers based on the subgrade CBR and the thicknesses of the layers. To select a layered system move the cursor to the layered system desired and press (ENTER) or click on it with a pointing device.

Pavement Performance Criteria (CRITERIA)

Five different pavement performance criteria have been developed and implemented into the ACNHS program. The criteria are based on the vertical deflection, vertical strain, maximum horizontal shear strain, maximum shear strain, and octahedral strain. The criteria were obtained from analysis of available data of full scale test sections conducted by the Corps of Engineers and other federal agencies. These criteria relate calculated response parameters (strains or deflections) computed at the top of the subgrade to the number of coverages that caused the test sections to fail. The following equations describe the linear regression curves for the response parameters implemented in the program.

Figure A6. Relationship between load and pavement response parameter in an elastic system

Single-Layer System Criteria:

Allow. Vertical Deflection: LOG_{10} (D_v) = $-0.5160-0.1635$ LOG_{10} (COVERAGES)
Allow. Vertical Strain: LOG_{10} $(_{vs})$ = $-1.9875-0.2043$ LOG_{10} (COVERAGES)
Allow. Max. Horiz. Shear Strain: LOG_{10} $(_{mhs})$ = $-1.9877-0.2000$ LOG_{10} (COVERAGES)
Allow. Max. Shear Strain: LOG_{10} $(_{ms})$ = $-1.8098-0.1992$ LOG_{10} (COVERAGES)
Allow. Octahedral Strain: LOG_{10} $(_{octs})$ = $-1.8335-0.2027$ LOG_{10} (COVERAGES)

Multi-Layer System Criteria:

Allow. Vertical Deflection: LOG_{10} (D_v) = $-0.6816-0.1355$ LOG_{10} (COVERAGES)
Allow. Vertical Strain: LOG_{10} $(_{vs})$ = $-2.2977-0.1549$ LOG_{10} (COVERAGES)
Allow. Max. Horiz. Shear Strain: LOG_{10} $(_{mhs})$ = $-2.3809-0.1452$ LOG_{10} (COVERAGES)
Allow. Max. Shear Strain: LOG_{10} $(_{ms})$ = $-2.1538-0.1504$ LOG_{10} (COVERAGES)
Allow. Octahedral Strain: LOG_{10} $(_{octs})$ = $-2.1772-0.1546$ LOG_{10} (COVERAGES)

Subgrade CBR Strength Category (SUBGRADE STRENGTH)

Options are provided in this input area to select the desired subgrade strength category or to input the subgrade CBR directly. The categories are: High (15 CBR), Medium (10 CBR), Low (6 CBR), and Ultralow (3 CBR). The user may select one strength category or may enter a suitable subgrade CBR value at the [CBR=_____] input field. Selecting one of the four standard categories automatically updates the [CBR=_____] field.

Traffic Coverage Level (COVERAGE LEVEL)

The standard traffic coverage level for ACN determinations is 10,000 coverages, which is automatically set when the programs starts. Any desired coverage level may be input directly in the data field.

Response Parameter Cutoff Distance (CUTOFF DISTANCE)

The cutoff distance allows the user to physically cut the influence of a response parameter at a certain distance away from the center of a load. The cutoff distance is expressed in terms of the radius of contact area of the tires in a gear assembly. The actual cutoff distance is the input distance plus the pavement total thickness. This cutoff distance varies with the tire imprint area and load. Some researches have used values that vary from 10 to 25 times the radius of contact area. If no cutoff distance is desired, the cutoff distance should be set sufficiently large to be greater than any distance from a grid node to the center of a loaded area.

Trail Pavement Section (THICKNESSES)

This section of input fields allows the user to enter the desired pavement thicknesses to represent the pavement section. The five input fields that make up this category are: [Total=_____], [Asphalt=_____], [Base=_____], [Subbase=_____], and [Calc. Depth=_____]. The user may enter the total pavement thickness and the computer program will automatically assign asphalt, base, and subbase thicknesses based on a "standard pavement section." This standard section is broken down as follows: Asphalt - 0.15 x Total, Base - 0.20 x Total, and Subbase = Total - Asphalt - Base. However, the user may change these values by typing the appropriate values in the input fields. The depth of calculation for the response parameters should be set to the total depth of the pavement because the performance criteria is based on the response at the top of the subgrade. The computer program will automatically set this value to the total thickness unless the asphalt, base, and subbase thicknesses are changed. The user must be certain that the calculation depth is at the correct depth.

Note: The program allows the user to determine deflections and/or strains at different depths by typing different values at the [Calc. Depth] field. However, the user must be aware that the allowable loads and ACN values calculated will not be based on appropriate criteria.

Load Data Files (DATA FILES)

The user can type in the name of a load data file or select one by pressing the [LOAD] button. Notice that this file must be already created by the ACNIN computer program discussed in previous sections.

Rigid Boundary Layer

By pressing the [CALC] button, one additional window will open (Figure A7) asking the user to enter or accept the depth to a rigid boundary. When using the layered elastic theory, it has been found in the past that surface deflection basins can be better matched if a rigid boundary is set at a depth of approximately 20 feet. The use of this rigid layer counter-acts the assumption that the subgrade layer extends downward to infinity. The user may enter the desired depth or press the [OK] button to accept the default value (240 inches). The user may press the [IGNORE] button if no rigid layer boundary is desired.

Button Menu

(1) [CALC] Button: Click on this button or press the (F10) key to start performing the calculations.

(2) [ACN RESULTS] Button: Click on this button or press the (F5) key to view any existing results saved on disk. When the calculations are performed by pressing the [CALC] button, this step is automatically performed.

(3) [HELP] Button: Click on this button or press the (F1) key to get an explanation on the input fields of this screen.

(4) [EXIT] Button: Click on this button or press the (F9) key to end this program and return either to the menu of programs or to the DOS prompt.
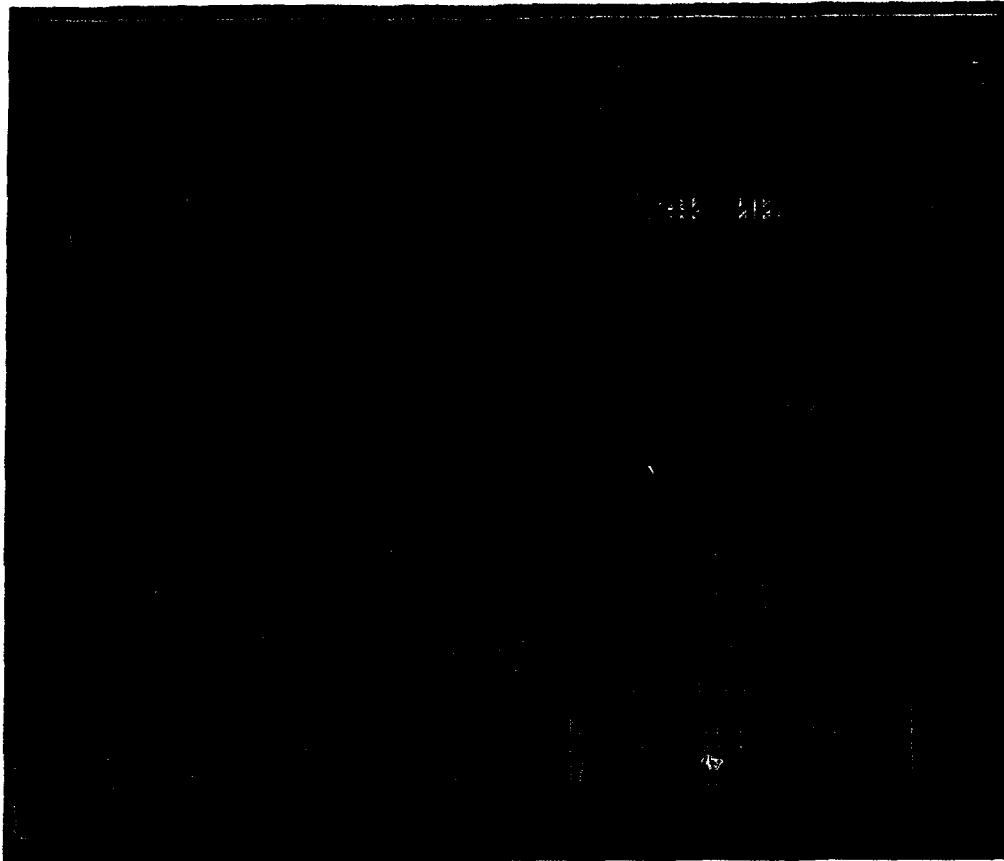
Figure A7. Screen for the rigid boundary layer depth

EXAMPLES DESCRIPTION

This section presents two step-by-step examples to illustrate the various features of the computer programs. In these examples, a pavement analysis is conducted for a B-747 twin-tandem gear (44 x 58 inches). The load on a single 4-tire gear is equal to 200,000 pounds and the tire pressure equal to 187.27 pounds per square inch. The allowable load is desired for a pavement thickness of 30 inches on a 15 CBR subgrade soil. The calculations are required to be based on the single-layer criteria and a cut-off distance equal to 10 radii. For the first example, a constant tire contact area is used.

For the second example, a constant tire constant pressure and a multi-layer analysis are used. Since the input of load data in the ACNIN program and the analysis parameters in the ACNHS program are common for both examples, the user may follow the first example to change appropriate parameters in the second example.

EXAMPLE PROBLEM 1

Running the Program

(1) The first step is to run the computer program. At the DOS prompt type: C > ACN. A menu of the programs is displayed as shown in Figure A1.

(2) Select the [Input Aircraft Loads] button to create a load data file by moving the cursor to the button and pressing (ENTER) or by clicking on it with a mouse. Press the (ENTER) key to continue at the welcome screen. The load data screen will be opened and ready for input.

Entering Load Data

(3) Move the cursor to the [Designation:] field (or click on it) and type: B747 Gear 200K.

(4) In this example the gross load is equal to the gear load. Move the cursor to the [Gross Load, GL (lbs):] field and type: 200000. Note: Move the cursor by pressing the (Tab), (Shift-Tab), or the (ENTER) keys.

(5) Move to the [Fraction of GL on gear to analyze:] field and type: 1.0. Note: The ratio (gear load/aircraft load) - 1.0.

(6) Move to the [Number of Tires in Gear (Max- 50):] field and type: 4.

(7) Move to the [Load Data File Name:] field and type: B-747200.LOA. This is the load data file that will be read by the ACNHS program to compute the ACN values and allowable loads.

(8) Press the [TIRE COORD.] button or press the (F2) key on the keyboard to enter the gear tire coordinates. At the next screen enter the tire coordinates as indicated in Figure A3. Notice that the origin of the coordinate system was located at the center of the gear. When finished entering the tire coordinates, press the [OK] button or the (F10) key on the keyboard to accept the input.

(9) The next step is to build the search grid. Since the gear is symmetric, only one quadrant needs to be gridded to compute the maximum response parameters. Figure A8 depicts the extension of the search grid for this problem. The search grid origin is conveniently set at the geometrical center of the gear. With the grid origin set at the center of the gear and by setting the number of lines along the X-axis to 21 and the X-increments to 2 inches, a distance of 40 inches (20 at 2 inches) is covered which will provide search points outside the outer tire. In the same manner, setting the number of lines along the Y-axis to 21 and the Y-increments to 2.6 inches, a distance of 52 inches is covered which is also beyond the tire. These X- and Y-increments also guarantee that at least one point is directly underneath a tire. To input this grid, move to the X- and Y- origin and enter zero in both fields. Enter a value of 21 for the number of lines in the [X- and Y-Lines] fields. Finally, enter a value of 2.0 inches in the [DX-Incr.] field and a value of 2.6 inches in the [DY-Incr.] field.

At this point the input screen should look like the one shown in Figure A2. To save this file, press the [SAVE] button or press the (F4) key. After the file has been saved, press the [EXIT] button or press the (F9) key to exit this program and return the menu of programs.

Specifying Calculation Parameters

Now that the load data file has been created, the ACNHS program can be executed. To execute the program select the [Compute ACN Values] button from the menu of programs (Figure A1). At the welcome screen press (ENTER) to continue. The main input screen is displayed.

(10) For this example, a constant tire contact area will be used. Move the cursor to the tire contact area in the [ASSUME CONSTANT] box and press (ENTER) or click on it with the mouse.

(11) In the same manner, select the single-layer criteria in the [LAYER SYSTEM] BOX.

> Note: Since the tire contact area was assumed to be constant, all the response parameters under the [CRITERIA] box will be calculated and presented in the results even though only one is selected. However, if the contact pressure is assumed to be constant, then the user must select only one of these response parameters in which the program is going to iterate on.
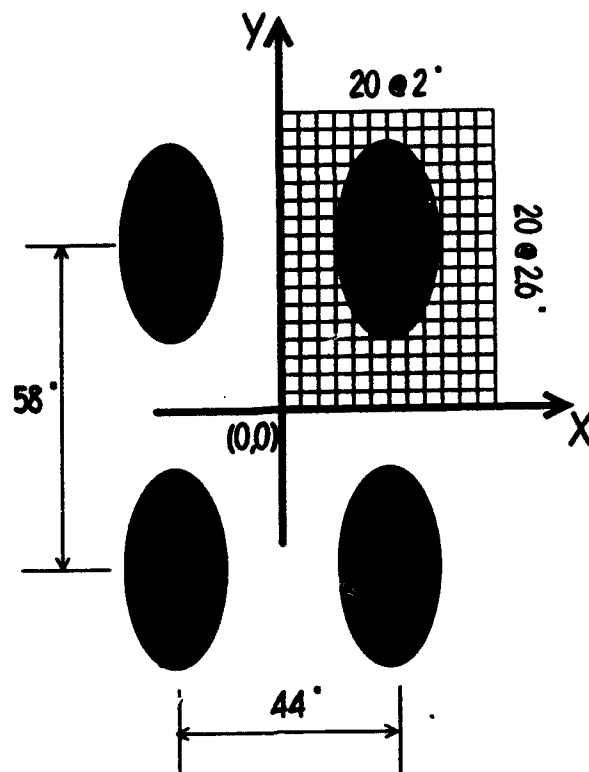
Figure A8. Extension of the search
grid for the example problems

(12) The subgrade CBR strength for this example is 15. Move the cursor
to high in the [SUBGRADE STRENGTH] box and press (ENTER) or alternatively move
to the [CBR=_____] input field and type 15.

(13) Since the ACN values are desired, a coverage level of 10,000 must
be used to obtain the ACN, which would correspond to the ICAO ACN. Move to
the [COVERAGE LEVEL] field and type 10,000.

(14) Move to the [In Radii] field of the [CUTOFF DISTANCE] box and
type 100.

(15) For this example problem the ACN values and aircraft allowable
loads will be determined for a 30-inch pavement. The ACN will correspond to
the allowable aircraft load. Move to the [Total=_____] field in the [THICK-
NESSES (in)] box and type 30. The program will automatically assign pre-
selected thicknesses for the asphalt, base, and subbase layer. Because in
this example the single-layer system will be used, there is no need to change
this values since all layers will have the same modulus of elasticity and
Poisson's ratio. However, if this were not the case, the user may type dif-
ferent thicknesses values for those layers. In addition, the computer program
will automatically assign the calculation depth in the [Calc Depth (in)] field
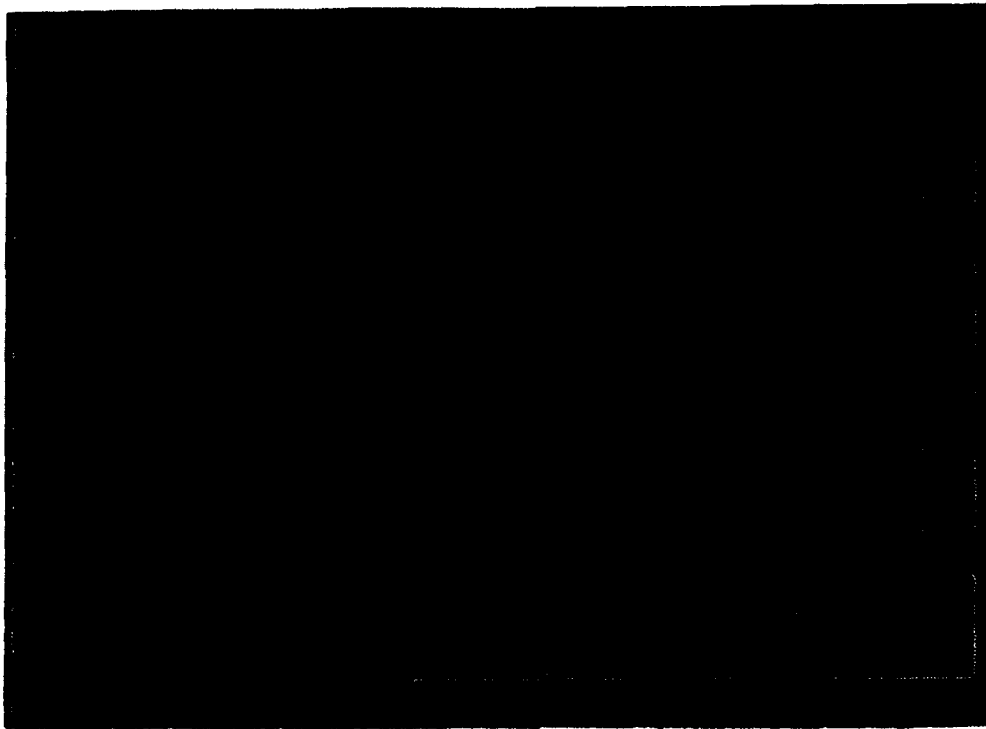to be equal to the total thickness of the pavement.

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Figure A9.   Example screen displaying a list of available
load data files

(16) The last input in this screen will be to select the load data file
for this problem. Press the [LOAD] button or press the (F4) .key to display a
list of available load data files. A screen similar to Figure A9 is next
displayed. Move the selection bar to the data file B-747200.LOA created
before and press (ENTER) twice. The user may also use the mouse to "scroll
down" the window if necessary, click of the file name, and press the [OK]
button or press the [F10] key. The program will come back to the previous
input screen. The screen should look like the one shown in Figure A5. Press
the [CALC] button or press the (F10) key to perform the calculations.

(18) A window asking about the rigid boundary layer is presented. Press
the [OK] button or press the (F10) key to accept the default value. A window
presenting the search grid status is displayed in the middle of the screen to
indicate the program is performing calculations.

Viewing ACN Results

After the calculations are performed, a window containing all results is
displayed. Figure A10 shows a partial view of the ACN results for the example
problem. The user may scroll up or down this window to view different parts
of the output by using the (UpArrow) or (DnArrow) keys or by clicking with the
mouse on the right scrolling bar. If the [PRINT] button or the (F3) key area
is pressed, a screen displaying available print options is shown as illu-
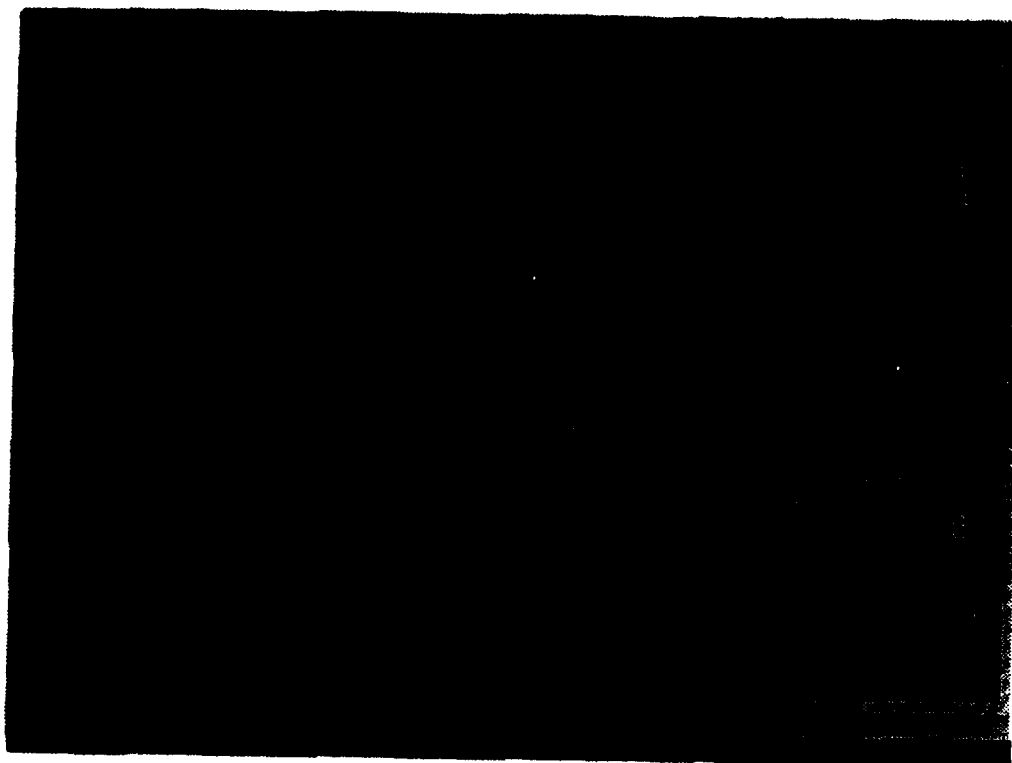strated in Figure A11. The print options are:

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Figure A10. Partial view of the ACN results for the example
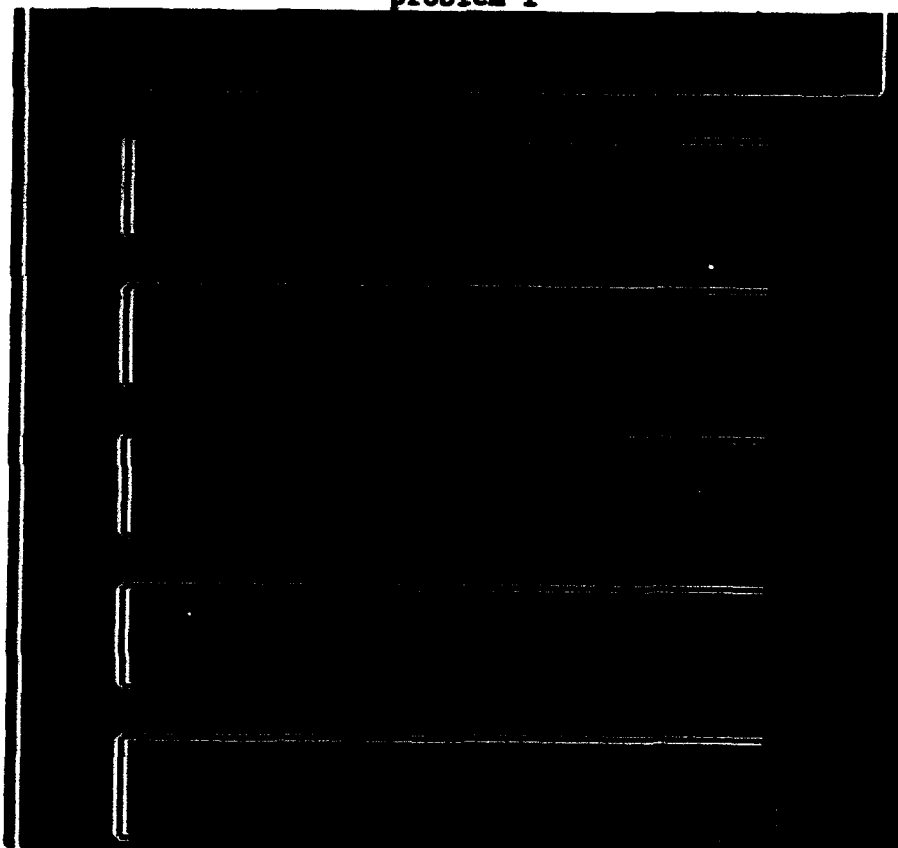problem 1

Figure A11. Available print options for the ACNHS
computer program

[ACN Results]: Only prints the ACN results.
[LOAD Data File]: Only prints the load data file use for the
calculations
[STRUCTURE Data File]: Only prints the pavement structure built by the
program   [ALL Data Files]: Prints all input and output data files
[CANCEL]: Cancels the printing operations and returns to the output
window

Brief Discussion of the Results of Example 1

Figure A12 contains a printout of all the input and output data files
generated by the program. The first few lines contain the load information,
pavement thickness, and subgrade CBR. The pavement PCN value and the allow-
able standard wheel load (which are based on the Corps of Engineers CBR equa-
tion) are printed. Since the analysis is for a constant area, the allowable
aircraft load, allowable single wheel load, allowable standard wheel load, and
the ACN values for all the performance criteria have been computed and are
displayed under the STRAIN CRITERIA heading. The allowable loads are computed
by:

Allow. Aircraft Load - Aircraft Load x
         (Allow. Response/Calculated Gear Response)
Allow. Single-Wheel Load - Tire Load x
         (Allow. Response/Calculated Single-Wheel Response)
Allow. Standard Wheel Load - Standard Wheel Load x
         (Allow. Response/Calculated Standard-Wheel Response)
ACN - (Allowable Standard Wheel Load /2.2/500)

where "response" stands for the pavement performance criteria used (i.e.,
deflection, vertical strain, etc.) and "allowable" stands for the permissible
deflection or strain from the performance criteria. These strain and deflec-
tion responses are presented in the next four columns following the allowable
load and ACN values table. Also printed are the locations where the maximum
values of these responses occur. The rest of this output file contains the
load data file and the pavement structure file used for the calculations.
Note that although only one aircraft was entered (the B-747 gear) this load
data file contains data for two aircraft. The first part of this section
contains the data that corresponds to the "standard single-wheel tire" used to
calculate the ACN values (calculations of ACN values are in reference to this
standard tire). The second section in this example output contains the actual
gear entered for the analysis. Finally, the pavement structure automatically
built by the computer program is printed. This section contains the layer
thicknesses, modulus of elasticity values, Poisson's ratios, and calculation
depth. Note that by assuming several trail pavement thicknesses (which in
turn corresponds to an allowable aircraft load), a plot of ACN versus allow-
able aircraft load can be constructed for a specific CBR strength category.

EXAMPLE PROBLEM 2

The same data in example 1 will be used in example 2 with the exception
of the layer system, performance criteria, and the use on a constant contact

```
         SINGLE-LAYER CRITERIA - CONSTANT TIRE CONTACT AREA
Aircraft                     = B-747 Gear 2
Initial Load (lbs)           =   200000.00
Depth(in)                    =       30.00
Subgrade CBR                 =       15.00
---- CBR EQUATION ----
Pavement PCN                 =      126.11
Allow. Standard Wheel Load   =   138718.97
Radii Cutoff Distance        =       10.00
Coverage Level               =    10000.00
---- STRAIN CRITERIA ----
  Performance     Allowable      Allowable     Allowable STD     ACN
  Criteria      AC Load(LBS)     AC SW Load     Wheel Load
-------------------------------------------------------------------------
Deflection        266052.62      113543.47      112603.45       102.37
Vertical Strain   309205.50       75653.03       74000.53        67.27
Horiz. Shear Strain 289863.45     90509.05       88709.95        80.65
Max. Shear Strain 307915.91       79585.68       77847.28        70.77
Octahedral Strain 305727.69       77394.70       75704.16        68.82

  Performance     Allowable       Gear       Single AC      Standard
  Criteria        Strain at      Strain      Tire  Strain    SW Tire
                Coverage Level   Response     Response       Response
-------------------------------------------------------------------------
Deflection        .6761E-01      .5082E-01    .2977E-01      .2402E-01
Vertical Strain   .1568E-02      .1014E-02    .1036E-02      .8475E-03
Horiz. Shear Strain .1630E-02    .1125E-02    .9007E-03      .7352E-03
Max. Shear Strain .2474E-02      .1607E-02    .1554E-02      .1271E-02
Octahedral Strain .2268E-02      .1484E-02    .1465E-02      .1199E-02

-- COORDINATES OF MAX. STRAIN OR DEFLECTION --
  Performance     X-Coord.       Y-Coord.
  Criteria        (in)           (in)
-------------------------------------------------------------
Deflection        14.00          23.20
Vertical Strain   22.00          29.00
Horiz. Shear Strain 32.00        40.60
Max. Shear Strain 22.00          31.90
Octahedral Strain 24.00          31.90
```

Figure A12. Printout containing the results of the example problem 1 (Continued)

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```
LOAD Data File
Job Title
STANDARD SINGLE WHEEL
No. of Aircraft
2
Aircraft Identification #  1
STANDARD-SW
Gross Load
 40000.00
Fraction of Gross Load on Gear to be analyzed
 1.0000
No. of Tires
1
Tire  Radius  Cont.Area  Cont.Press.   Tire Load   X-coord.  Y-coord.
No.   (in)    (sq.in)    (psi)         (pounds)    (in)      (in)
-------------------------------------------------------------------
1    8.383    220.766    181.1875      40000.00      .00       .00
Search grid
X-Origin   Y-Origin  No.X-Incr  DX-size   No.Y-Incr  DY-size
   0.0        0.0       30        1.00        1         1.00
Aircraft Identification #  2
-747 Gear 200K
Gross Load
200000.00
Fraction of Gross Load on Gear to be analyzed
 1.000
No. of Tires
4
Tire  Radius  Cont.Area  Cont.Press.   Tire Load   X-coord.  Y-coord.
No.   (in)    (sq.in)    (psi)         (pounds)    (in)      (in)
-------------------------------------------------------------------
1    9.22    266.99     187.27        50000.00    -22.00    -29.00
2    9.22    266.99     187.27        50000.00     22.00    -29.00
3    9.22    266.99     187.27        50000.00    -22.00     29.00
4    9.22    266.99     187.27        50000.00     22.00     29.00
Search grid
X-Origin   Y-Origin  No.X-Incr  DX-size   No.Y-Incr  DY-size
  .00        .00        21        2.00       21        2.90


 STRUCTURE Data File
 Job Title
 STANDARD SECTION
 Number of Pavements
  1
 Number Thicknesses & Moduli Variations
   1          1
 Pavement Description
 Flexible Pavement
 Slab Flexural Strength (only for rigid pavements)
 0.00
 No. of Layers
  3
Layer      Thicknesses    Modulus of    Poissons   Interface
Number       ( in )       Elasticity    Ratio      Condition      Layer Code
                          ( psi )
-----------------------------------------------------------------
   1          30.00        22500.00        .50                        0
                                                        .00
   2         210.00        22500.00        .50                        0
                                                        .00
   3                      1000000.00       .50                        0
No. of Depths
  1
Depth No.        Depth (in)
-----------------------------------
   1            30.00
```

Figure A12.   (Concluded)

pressure. The desired layer system is the multilayer criteria, constant contact pressure will be used, and the analysis will be performed for the maximum shear strain response parameter.

(1) Following the selection procedure described in example 1, select the Constant Pressure option in the ASSUME CONSTANT box (refer to Figure A13).

(2) Select the Multi-Layer Criteria option in the [LAYER SYSTEM] box and the Max. Shear Strain option in the [CRITERIA] box (refer to Figure A13). All other calculation parameters remain the same.

(3) Press the [CALC] button to perform the calculations. Since in this example the tire contact pressure was assumed to be constant, the program needs to perform an iterative procedure as mentioned earlier and will take more time to complete the calculations.

(4) A window asking about the rigid boundary layer is presented. Press the [OK] button or press the (F10) key to accept the default value. A window presenting the search grid status is displayed in the middle of the screen to indicate the program is performing calculations.

(5) After the calculations are done, a screen showing the results is displayed as illustrated in Figure A14. The user may scroll up and down the data window to revise the results. Notice that in this example, only the results for the selected response parameter (max. shear strain) are presented.

(6) If desired these results can be printed by pressing the [PRINT] button shown in Figure A14. Figure A15 contains a printout of the results of this example.

Brief Discussion of the Results of Example 2

Under the STRAIN CRITERIA heading (refer to Figure A15) the allowable standard load, aircraft ACN, allowable aircraft load, and calculated allowable strains are printed. Since the run is for a constant pressure, the results are for only one criteria. The allowable standard load is the load on the standard single-tire that will give a calculated strain equal to the permissible maximum shear strain given by the criteria. The tire characteristics of the standard tire are used to determine this strain. On the other hand, the allowable aircraft load is based on the gear characteristics of the aircraft and is also defined as the load that will give a calculated strain equal to the permissible strain. From the allowable standard load the aircraft ACN value is computed using the equation:

ACN = (Allowable Standard Load /2.2)/500

At the end of Figure A15 the pavement structure data file for this example is presented. Notice that in this case the pavement section is composed of seven different layers with modulus of elasticity and Poisson's ratio values assigned individually. Also, notice that the rigid boundary is set at 240 inches deep and has a preassigned modulus value of 10,000 psi.

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Figure A13. ACNHS input for example problem 2

Figure A14. Partial view of the results obtained for example problem 2

```
MULTI-LAYER SYSTEM - CONSTANT PRESSURE
MAX. SHEAR STRAIN CRITERIA
Aircraft                            =  B-747 Gear 2
Initial Load (lbs)                  =   200000.00
Depth(in)                           =       30.00
Subgrade CBR                        =       15.00
---- CBR EQUATION ----
Pavement PCN                        =      126.11
Allow. Standard Wheel Load (lbs)    =   138718.97
---- STRAIN CRITERIA----
Radii Cutoff Distance               =       10.00
Coverage Level                      =    10000.00
Allow. Standard Load                =    99682.46
Aircraft ACN                        =       90.62
Allowable Aircraft Load (lbs)       =   333566.71
Calculated Strain                   =     .1755E-02
Allowable Strain                    =     .1756E-02
-- COORDINATES OF MAX. STRAIN OR DEFLECTION --
X-Coordinate (inches)               =      22.0000
Y-Coordinate (inches)               =      31.9000




LOAD Data File
Job Title
STANDARD SINGLE WHEEL
No. of Aircraft
2
Aircraft Identification #  1
STANDARD-SW
Gross Load
 40000.00
Fraction of Gross Load on Gear to be analyzed
 1.0000
No. of Tires
1
```

Tire No.	Radius (in)	Cont.Area (sq.in)	Cont.Press. (psi)	Tire Load (pounds)	X-coord. (in)	Y-coord. (in)
1	8.383	270.766	181.1875	40000.00	.00	.00

```
Search grid
```

X-Origin	Y-Origin	No.X-Incr	DX-size	No.Y-Incr	DY-size
0.0	0.0	30	1.00	1	1.00

```
Aircraft Identification #  2
-747 Gear 200K
Gross Load
200000.00
Fraction of Gross Load on Gear to be analyzed
 1.000
No. of Tires
4
```

Tire No.	Radius (in)	Cont.Area (sq.in)	Cont.Press. (psi)	Tire Load (pounds)	X-coord. (in)	Y-coord. (in)
1	9.22	266.99	187.27	50000.00	-22.00	-29.00
2	9.22	266.99	187.27	50000.00	22.00	-29.00
3	9.22	266.99	187.27	50000.00	-22.00	29.00
4	9.22	266.99	187.27	50000.00	22.00	29.00

```
Search grid
```

X-Origin	Y-Origin	No.X-Incr	DX-size	No.Y-Incr	DY-size
.00	.00	21	2.00	21	2.90

Figure A15. Printout containing the results of the example
problem 2 (Continued)

```
STRUCTURE Data File
Job Title
STANDARD SECTION
Number of Pavements
  1
Number Thicknesses & Moduli Variations
  1           1
Pavement Description
Flexible Pavement
Slab Flexural Strength (only for rigid pavements)
0.00
No. of Layers
  7
```

Layer Number	Thicknesses (in)	Modulus of Elasticity (psi)	Poissons Ratio	Interface Condition	Layer Code
1	4.50	250000.00	.50		0
				.00	
2	6.00	64048.04	.30		0
				.00	
3	6.50	37361.73	.30		0
				.00	
4	6.50	34554.78	.30		0
				.00	
5	6.50	29644.20	.30		0
				.00	
6	210.00	22500.00	.40		0
				.00	
7		1000000.00	.50		0

```
No. of Depths
  1
```

Depth No.	Depth (in)
1	30.00

Figure A15.   (Concluded)

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The test data for performance of flexible pavements were collected, sorted, and tabularized. The test data were analyzed using Boussinessq and layered elastic pavement models. To assist in the analysis, two computer programs were developed. The first program used the Boussinessq model to compute equivalent single-wheel loads. This program will compute the equivalent single-wheel load considering any selected cutoff distance. The second program used layered elastic theory for the analysis of pavements structures. The program has the capability of determining maximum pavement response for several response parameters, determining allowable loads for selected performance criteria, and computing a new layered elastic aircraft classification number. Several different performance criteria were developed including deflection criteria employing different cutoff distances, and strain criteria determined from the layered elastic

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17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
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13. ABSTRACT (Continued).

pavement model. It was shown that deflection and strain criteria could be developed for the design of heavy multiwheel aircraft which would be independent of the number of tires in the aircraft gear. Performance criteria based on deflection, vertical strain, horizontal shear strain, maximum shear strain, and octahedral strain were incorporated into the layered elastic computer program to give predictions for pavement performance. Comparisons of the strain criteria were made with the current design criteria.

The indications are that the current U.S. Army Corps of Engineers (USACE) California Bearing Ratio (CBR) design procedure gives pavement thicknesses that are overly conservative for very low subgrade CBR values, but are inadequate for high subgrade CBR values. A new procedure is suggested for computing the aircraft classification number which would be based on an equivalent pavement response parameter.

14. SUBJECT TERMS (Continued)

Aircraft classification number	Full-scale test section
Airport pavement design	Multiwheel aircraft
California bearing ratio	Pavement analysis
Coverages	Pavement design
Elastic layered theory	Pavement performance criteria
Equivalent single-wheel load	